2009

Computer-Assisted Emergency Evacuation Planning Using TransCAD: Case Studies in Western Massachusetts

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COMPUTER-ASSISTED EMERGENCY EVACUATION PLANNING USING TRANSCAD: CASE STUDIES IN WESTERN MASSACHUSETTS

A Thesis Presented

by

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Submitted to the Graduate School of the
University of Massachusetts Amherst in partial fulfillment
of the requirements for the degree of

MASTER OF SCIENCE IN CIVIL ENGINEERING

September 2009

Civil and Environmental Engineering

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ACKNOWLEDGEMENTS

I would like to express my utmost appreciation for UMass Amherst and all of the support it has given me over the duration of my course work and thesis writing. The support staff was crucial in assisting me with the preparation of this thesis, and they were helpful in countless other ways.

The three professors I worked with on this thesis, Daiheng Ni, Song Gao, and John Collura, provided excellent input and always helped out whenever I had a question to ask. They were a valuable sounding board to make sure I was staying on track with the research.

This work was completed with the help of two other graduate students: Xuan Lu and Haizhong Wang. It was a great pleasure to work with both of these individuals during the duration of the project. Several other students also helped with portions of the project as well, and I would also like to thank these students.

Without the dada provided by the PVTA, FRCOG, and BRPC, this thesis would not have happened. The representatives from these agencies deserve a thousand thanks for providing valuable input and feedback. The meetings I had with these groups helped me develop my presentation skills, along with giving valuable contacts in the region.

I would also like to thank all of the other graduate students that kept me motivated during the late night hours. They kept the time I spent here both interesting and enjoyable. I would also like to thank my family and loved ones who made the transition into UMass-Amherst and Massachusetts in general easy and enjoyable.

Chelsea Humbyrd deserves special thanks for all of the time she spent proofreading this thesis.

ABSTRACT

COMPUTER-ASSISTED EMERGENCY EVACUATION PLANNING USING TRANSCAD: CASE STUDIES IN WESTERN MASSACHUSETTS

SEPTEMBER 2009

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Disasters, ranging from manmade events to natural occurrences, can happen anywhere on the planet, and their consequences can range from economic loss to catastrophic loss of life. Determining how the transportation system fares in the face of these disasters is important so that proper planning can take place before, rather than after, an event has happened. Modeling the transportation system gives operators the ability to discover bottlenecks, to determine the possible benefit of using lane reversals, and to find out the influence of evacuation speed on system efficiency. Models have already been created that are able to model some of these types of disasters with some level of accuracy. These models range from microscopic simulation to regional, macroscopic models. This research examines how an off-the-shelf regional modeling software package, TransCAD, can be used to model emergency evacuations. More specifically, this thesis presents four case studies involving three different types of disasters in Western Massachusetts. Because this research documents a first-hand experience using TransCAD in emergency evacuation planning, the results give regional

modelers the ability to modify their models to fit their specific region. These case studies demonstrate how the modified inputs and existing portions of the four-step transportation planning model can be used in place of the usual data demands of the software. Dynamic traffic assignment is used in three of the case studies while the fourth case study uses static traffic assignment. An evaluation of the software package along with lessons learned is provided to measure the performance of the software.

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CHAPTER 1

INTRODUCTION

1.1 Motivation

Disasters and other events often happen very quickly and proper planning must be undertaken to mitigate their effects. In some of these situations, an evacuation must be ordered to help ensure the safety of the citizens living in the path of the danger. As has been shown with Hurricane Rita, which struck Texas in late 2005, evacuations can take a toll on the transportation system. It was reported that some evacuees moved only ten to twenty miles in nine hours (this equates to about one to two miles per hour) (Blumenthal 2005). There were reports of trips from Houston to Dallas and San Antonio taking sixteen hours, four times longer than normal. Government officials strongly encouraged people to evacuate partially in order to avoid a catastrophe similar to the one that befell the citizens of New Orleans a few weeks prior. Several weeks before Hurricane Rita, Hurricane Katrina devastated New Orleans, and this event was still fresh in everyone's minds. The government's urgency and the recent memories of Hurricane Katrina combined to create one of the largest evacuations in the history of the United States. Contraflow lanes were opened to increase capacity, but this was too little, too late for the unprecedented demand. Many of the deaths attributed to Hurricane Rita were not caused by the hurricane itself, but rather by events surrounding the storm (including car accidents, fires, and illness). Extraordinary delays can potentially cause many secondary problems such as becoming ill or worse from a lack of food or water. In the Midwest, states have suffered several floods due to severe weather events in the years of 2007 and 2008. In the more recent flood, the damages totaled billions of dollars, and there were many fatalities. There are many more examples of disasters besides hurricanes and floods that can, and should, be examined. With proper planning, these events' disastrous effects can be mitigated.

Every area in the world can face some type of disaster. For this reason, it is important for all planning agencies and emergency managers to be prepared to make decisions regarding what to do if a potential disaster occurs. Emergency managers use a four-step process that includes *mitigation*, *preparation*, *response*, and *recovery*. The transportation system is, to varying degrees, a component of all of these steps. In the *mitigation* step, planners want to make policy decisions before the disaster to minimize the threat to human life and property (Godschalk 1991); these policies relate to the transportation system through the implementation of a designated evacuation route. *Preparedness* is the development of operational capabilities and the facilitation of an effective response (Godschalk 1991). Implementing message signs (VMS) that would inform drivers of road conditions is an example of *preparedness*. *Response* denotes the actions taken immediately prior to, during, or after the emergency to save lives (Godschalk 1991); the use of the roadway for both evacuation and for emergency responders heading into harm's way is an example of *response* relating to the transportation system. *Recovery* is the returning of the environment to normal levels (Godschalk 1991). During the *recovery* phase there needs to be reconstruction of the roadway facilities along with the use of the roads by construction and maintenance crews assisting in the rebuilding of the affected communities.

This document helps answer the question of how well the four-step transportation modeling process (along with GIS-based transportation software) can be adapted for the use of modeling evacuations or other emergency management actions. Three main steps were taken for this evaluation:

- Develop models and methods to adjust the malleable portions of the four-step planning model with the goal of replicating the thought processes and actions of the affected residents during a disaster.
- Run the models on four different case studies: a chemical spill, a flood caused by a dam failure, a hurricane affecting a solitary county, and a hurricane affecting multiple counties or regions.
- Evaluate the ability of the software to accept the adjusted inputs, along with estimating the feasibility of the results.

1.2 Organization

This document is organized into nine chapters. The next chapter (Chapter 2) contains a literature review. This chapter gives context to the modeling exercises by providing a general background on emergency management and disasters, discussing existing evacuation models, and showing where this document fits into evacuation planning and emergency management. Following this chapter is the data chapter (Chapter 3). This chapter discusses the three region's data. Following this, a general methodology for the rest of the thesis (Chapter 4) is laid out. The next three chapters are case studies that can be read independently of each other. These case studies separately examine a chemical spill (Chapter 5), a flood caused by a dam failure (Chapter 6), and a single county hurricane evacuation (Chapter 7). The subsequent chapter (Chapter 8) is another application of the methodology laid out in the hurricane evacuation chapter. This chapter provides a reality check to give context to the first hurricane scenario. The final chapter contains discussion and conclusions (Chapter 9). This chapter considers the areas that TransCAD performed well or poorly, and presents lessons learned in the process of modeling the various scenarios.

CHAPTER 2

LITERATURE REVIEW

2.1 Background on Emergency Management

Researchers in the field of emergency management have classified disasters into four categories: natural, technological, civil, and ecological (Hoetmer 1991). Natural disasters are disasters found in nature, which would occur without human intervention. Some common natural disasters are tornados, hurricanes, severe snowstorms, and earthquakes. A technological disaster is caused by human omission or error (Hoetmer 1991), for example a nuclear release or a chemical spill resulting from a traffic incident. A civil disaster, however, is a disaster deliberately caused by humans (Hoetmer 1991), such as a terrorist strike or a war. This differs from a technological disaster primarily in the motivation. The final disaster type, ecological, includes items such as the destruction of rainforests or the gradual leaking of chemicals into the environment. A main characteristic of this type of disaster is the slow disruption or waste of resources that gradually causes widespread problems.

As previously mentioned, the civil disaster category includes wars and terrorist actions. A war causes a fundamental shift in the entire transportation system, and would need a completely new regional model to replicate. However, a localized terrorist strike would be of concern in this thesis. An ecological disaster could be modeled in the same as a civil (specifically, war) disaster, the productions and attractions of the model would need to be recalculated in the normal way due to the shift in activity centers. This thesis is mostly considered with short-term evacuations; therefore, slow occurring, long-term shifts resulting from a civil or natural disaster are not considered.

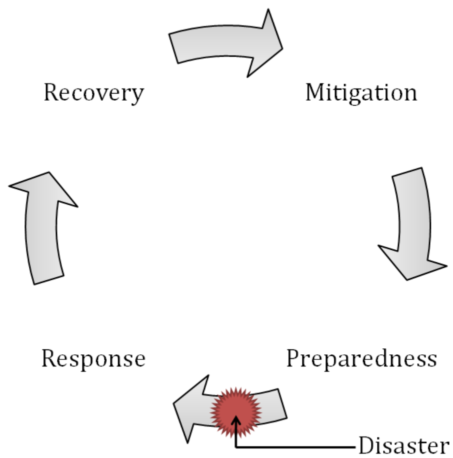

Figure 1 Emergency management cycle (adapted from (Drabek 1991)).

Emergency management professionals utilize a four-step process consisting of preparedness, response, recovery, and mitigation. Each of these four steps is important in its own right. Preparedness involves the training of personnel, dissemination of information to the public, and other tasks that create a more effective response. Response involves the actual evacuation efforts, rescue efforts, and the deployment of support personnel. Recovery is the process of restoring the damaged area back to a stable state. Mitigation is the attempt to reduce the damage that occurs as a result of a disaster; for instance, mandating a restriction on what can be built inside of a flood plain or dam inundation area with the goal of limiting the at-risk population (Godschalk 1991). This cycle is shown in Figure 1. The cycle can begin at any point, but ideally, planners would start before the disaster strikes at preparedness or mitigation, with the latter being more preferable.

2.2 Behavior of Evacuees

In popular media, evacuees are often characterized as disorganized and frantic (Scanlon 1991). In part, this has caused the concern that people will react in a panicked flight, defined by Quarantelli as "an acute fear reaction marked by loss of self-control which is followed by a non-social and non-rational flight behavior" (Quarantelli 1954). Quarantelli also shows that people might panic if they find that their escape options are closing off over time or if they feel they have no ability to affect their outcome (Quarantelli 1954). This is simply not found in disasters. Some cases of panic can be explained through "observer error"; in other words, people observing those leaving the scene of a disaster describe the situation as panicked without witnessing the entire situation. In the larger scope, people may actually be departing quite orderly. Several researchers have determined that victims help their families, neighbors and co-workers, panic is rare, looting is rare, and people with emergency responsibilities do their jobs and do not leave their posts (Scanlon 1991, Perry 1991).

Referencing specific evacuations, there is a series of studies performed by the U.S. Army Corps of Engineers (USACE) and the Federal Emergency Management Agency (FEMA) that outlines some of the behavioral responses of hurricane evacuees (HES 2003). These reports supply a strategy to cover many different response rates; for instance, Alabama (along with several of the other participating states) recommended the evacuation response rate range shown in Figure 2. Using post-evacuation reports, Alabama determined that the same people would leave quickly or slowly depending on the threat (AL HES 2001). This allows for the use of three curves to represent the same population (see Figure 2). The groups leaving quickly in one situation also leave quickly in the next situation. They also found that people would leave before an evacuation order has been called, but the rate is less than ten to twenty percent (AL HES 2001, MS HES 2001).

These curves may be somewhat affected by the perceived severity of the storm. The Saffir-Simpson Intensity Scale was developed in order to classify the severity of hurricanes. This scale is shown in Table 1, adapted from the National Weather Service website (NWS 2008).

Table 1 Saffir-Simpson Hurricane Intensity Scale

Category	Wind Speed (mph)	Damage
I	74-95	Poorly constructed signs, power outages, uprooted trees
II	96-110	Roofing material, windows, doors, widespread power outages
III	111-130	Minor wall failure, high rise windows, total power loss
IV	131-155	All signs down, mobile homes destroyed, most trees snapped
V	>155	Complete building failure, extended power loss

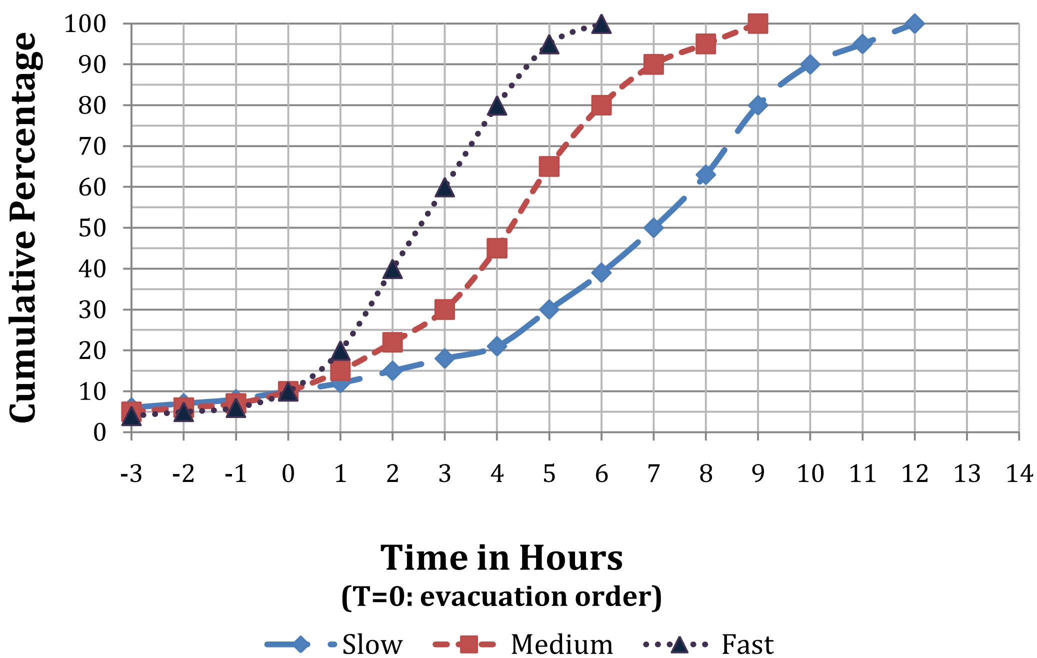

Figure 2 Evacuation rates used in USACE hurricane evacuation reports.

This scale classifies a storm by the speed of the wind associated with it. If the wind speed is below 74 miles per hour, the storm is classified as a tropical storm. The severity and the damage of the storm increases as the wind speed increases. A category I hurricane generally causes some minor damage to shrubbery and signs, while at the other end of the scale during a category V hurricane many roofs are destroyed, mobile homes are demolished, and windows and doors are damaged (NWS 2008).

2.3 Spatial Implications of a Disaster

The problems that result from disasters are spatial by their very nature (Godschalk 1991, Cova 1991). In the event of a chemical spill programs such as RMP*Comp are available that determine the extent of a chemical release based on the specific type and amount of a substance. Using this type of information in conjunction with Geographic Information Systems (GIS) can give emergency management practitioners a useful tool to aid them in planning. GIS can be used to help map out where the hazard area might be along with the vulnerability of area to arrive at a relative risk for each area (Cova 1991). Generally, researchers use the vulnerability of an area to determine whether to evacuate (Chakraborty, Tobin and Montz 2005, Jones and Andrey 2007). Chakraborty et al. use maps that were derived from insurance companies risk analyses, but note that if these maps are in highly erosive areas then geotechnical characteristics will change (Chakraborty, Tobin and Montz 2005). They create a set of overlays using GIS depicting social vulnerability, geospatial risk, and areas that need the most evacuation assistance.

2.4 Disasters and Transportation

Hurricane evacuation modeling gained interest in the 1970's and then the field's focus shifted towards nuclear disaster evacuations (Wilmot and Mei 2004). Following the three-mile island disaster in 1979, NETVAC was developed to address the modeling of evacuating traffic on a macroscopic level (Sheffi, Mahmassani and Powell 1982). Another model, DYNEV, came along a few years later and modeled the evacuation response to a nuclear disaster (KLD Associates 1984). Following these two nuclear evacuation models, two hurricane evacuation modeling tools were released: MASSVAC in 1985 (Hobeika and Jamie 1985) and HURREVAC in 1994 (COE 1994).

In general, these models estimate the number of households that would evacuate based on their proximity to the vulnerable area and type of housing (such as a mobile home or a typical house) (Wilmot and Mei 2004). These rates may account for the strength of the hurricane (Wilmot and Mei 2004). Several models use logistic regression to determine the participation rates (Irwin and Hurlbert 1995, RDS 1999). These papers contain variables that may help explain evacuation behavior, but they are not good variables to predict future scenarios because not all of the variables are measurable (Wilmot and Mei 2004). Some of the parameters that cannot be easily measured are perception of harm, perception of a home's durability (Irwin and Hurlbert 1995), and whether the neighbors have evacuated (RDS 1999). The next step involves the time dependant mobilization curve. These curves are often obtained using past hurricanes as a reference point. An example of these curves obtained from a series of USACE reports is presented in Figure 2.

2.5 The Four-Step Model and Evacuation Modeling

The four-step model is broken up into four parts: trip generation, trip distribution, mode-split, and traffic assignment. TransCAD, made by Caliper Corporation, provides transportation planners with a broad set of tools that help implement the four step planning model and analyze its results. This research completes a macroscopic simulation of what may occur in the event of an evacuation. Many researchers have delved into some of these steps already. A sample of the work completed on each section (except for mode-split, which is not considered) is presented in the following sections.

2.5.1 Trip Generation

Trip Generation determines how many trips are produced within a transportation analysis zone (TAZ) and how many trips are attracted to a TAZ. A TAZ is a homogenous area that is generally smaller than a census tract. These values can be based on demographic data such as vehicle ownership or employment. Fu and Wilmot use a sequential logit model, which uses the utility of evacuating for each TAZ, to model the trip productions. While generating productions for a hurricane, the authors use the characteristics of the storm rather than the characteristics of the people. Items included in their analysis include the speed of the storm, time of day of the evacuation, perception of receiving an evacuation order, and the ownership of a mobile home (Fu and Wilmot 2004). No demographic types of data are included. Other researchers use behavioral data as the basis of trip productions. Lindell and Prater list nine sources of behavioral information than can assist in the determination of the number of evacuees (Lindell and Prater 2007). Lindell and Prater use separate equations for transients and residents. Their generation equation relates the number of people and the location of those people inside the vulnerable area (Lindell and Prater 2007).

The research on where people evacuate to is more scarce. One group of researchers determined that certain areas would be used as refuges of last resort (RLR) (Schmidlin, et al. 2005). These areas include parking garages, subway stations, and other non-shelter locations. An RLR has the characteristics of there being no certainty that there will be food, water, or safety (Schmidlin, et al. 2005). It is a place that evacuees can use to provide minimal shelter. Lindell and Prater define two types of evacuation zones: proximate and ultimate. The proximate destination is where the trip leaves the risk area, and the ultimate destination is where the trip ends (Lindell and Prater 2007). The results from the trip generation step are used in the trip generation step of the four step planning model.

2.5.2 Trip Distribution

Trip distribution is the determination of where trips will go. In regional planning this is usually completed with a gravity model along with a friction factor function. Several groups have conducted research on trip distribution. In two papers Murray-Tuite and Mahmassani discuss many of the characteristics of trip distribution (Murray-Tuite and Mahmassani 2003, Murray-Tuite and Mahmassani 2004). They examine activity chains on the evacuation behavior and show that when a household evacuates they gather all of the residents before picking up their children in the most efficient manner (Murray-Tuite and Mahmassani 2003). Guangxiang has attempted to calibrate friction factors for use in the gravity model (Guangxiang 2007). In this research, the author uses a negative exponential function coupled with a Rayleigh distribution to model the trip distribution. Liu et al. use a cell transmission model to determine the trip distribution (Liu, Lai and Chang 2006). This model converts the network into cells that can be traversed in a unit of time.

2.5.3 Traffic Assignment

Traffic assignment determines what routes the trips will take. Regional models generally use a static traffic assignment (STA) and either a system equilibrium or user equilibrium algorithm. Many studies have been completed using STA. In the time of day step of the traffic assignment process, many researchers assume a sigmoid shape for the hourly traffic demand (Fu and Wilmot 2004). This shape, shown in Figure 2, represents the idea that people will tend to want to evacuate in the daylight hours. This shape is discussed in detail in Lindell and Prater 2007. Andem conducted a study on the comparison of STA against dynamic traffic assignment (DTA) for the use in hurricane modeling. Andem determined that it is feasible to use DTA for large networks (Andem 2006). Andem also noted that the DTA estimate is considerably higher for the roadway segments that he selected; this is in contrast with STA, which he concludes tends to drastically underestimate the volumes (Andem 2006). Once the results from the traffic assignment are obtained analysis of the results can begin.

2.6 Contributions

To our knowledge, this thesis contributes to emergency evacuation modeling in the following respects:

- By creating a method of generating productions and attractions using readily available, aggregate data for both a hurricane and a flood.
- By reviewing the use of a currently available regional modeling software package to model the evacuations.
- By determining what types of data can be obtained that may be useful to emergency management professionals using this software package and the created models.
- By providing first-hand experiences using TransCAD in emergency evacuation modeling, which allows transportation modelers to adapt the experiences to their specific modeling scenarios.

CHAPTER 3

DATA

Building a transportation model has significant data requirements. In general regional planning, models use combination of data types including number of vehicles, number of households, income, household size, and age, amongst a slew of other characteristics. Sometimes this data is highly disaggregate giving a very broken down categorization of the data. For instance, the data may show that there are two-hundred households making 100k +, one-hundred making 40-100k, and three-hundred earning less than 40k. Other data sets may simply record this as a total of six-hundred households. Another important set of information for modeling a transportation network are data about the network itself. This includes items such as number of lanes, free flow speed, speed limit, capacity at different levels of service, and functional classification, amongst other characteristics. Travel time distributions are required to calibrate the gravity model, which is often used in regional planning for trip distribution. Alternatively, factors may have already been calibrated that serve for replicating the trip length distribution data requirement.

The three regional planning agencies/council of governments are the Pioneer Valley Planning Commission (PVPC), the Franklin Regional Council of Governments (FRCOG), and the Berkshire Regional Planning Commission (BRPC). Each of them provided their fully functioning regional transportation models. The PVPC is composed of Hampshire and Hampden Counties, FRCOG is the council of government for Franklin County, and the BRPC is the planning commission for Berkshire County. An overview map of these counties is shown below in Figure 3, and a more detailed map of the three regions is shown in Figure 4. This document uses the terminology “three region” and “four county” interchangeably to refer to the area of concern. The three-region term accounts for the PVPC overseeing the planning activities for two counties, while the four-county term does not account for this.

The BRPC and FRCOG models had aggregated much of their data while the PVPC data is more disaggregate. The FRCOG and PVPC both use friction-factor lookup tables for the three modeled trip types (home-based work (HBW), home-base non-work (HBNW), and non home-based (NHB)) in the gravity model, while the BRPC uses the exponential model with different values for the coefficient in the exponential model equation during the gravity model.

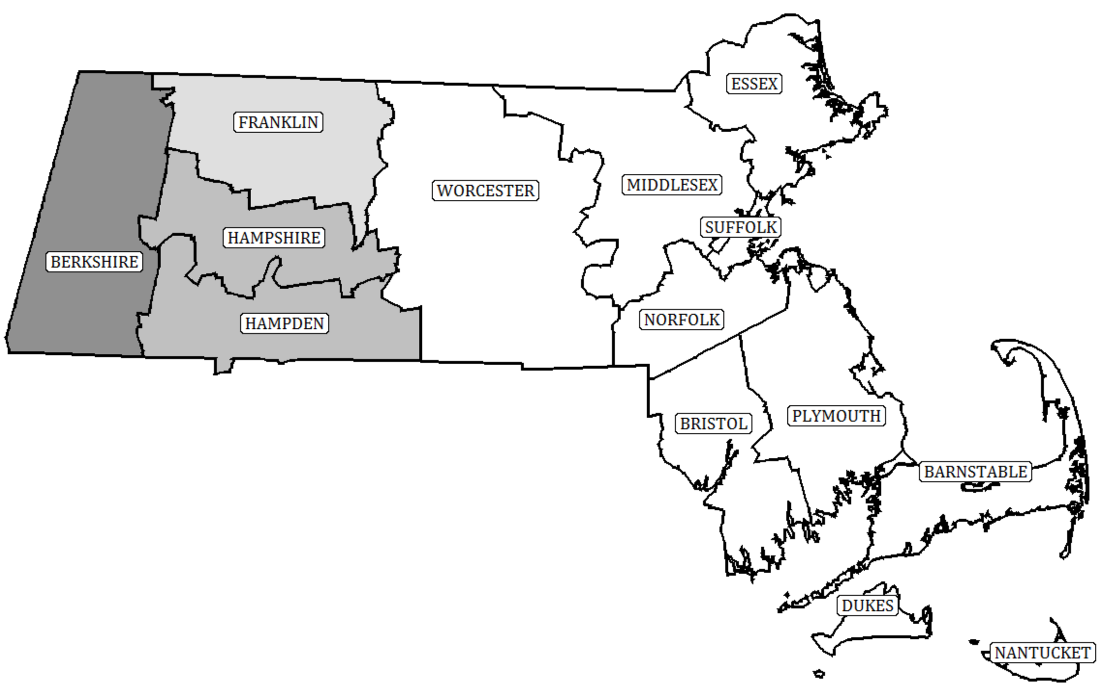

Figure 3 Massachusetts shown with the relevant counties shaded.

As mentioned in the introduction, four case studies are examined: (1) a chemical spill, (2) a dam failure and the resulting flood, (3) a hurricane that only affects a single county, and (4) a hurricane that affects several counties. In three of these scenarios (the chemical spill, dam failure, and single-county hurricane), the disaster is modeled exclusively within the region; therefore, the differences in the data formats or coefficients is not an issue. In the fourth scenario (the multi-region hurricane), the three regions' data sets are stitched together. There are some differences in the methods the regional planning agencies used to calculate the capacity of the links (or road segments). Depending on which side of the county line the link is, the capacity may drop or increase. In many of the test cases the daily capacity differs significantly, but the hourly capacity difference is either zero or very low. As noted earlier, the three regions also used different methods to calculate the friction-factor in the trip distribution step. Ideally, a new model would be developed for the entire region that would take into account the broader scope of the network. This topic is covered in more detail in Chapter 8.

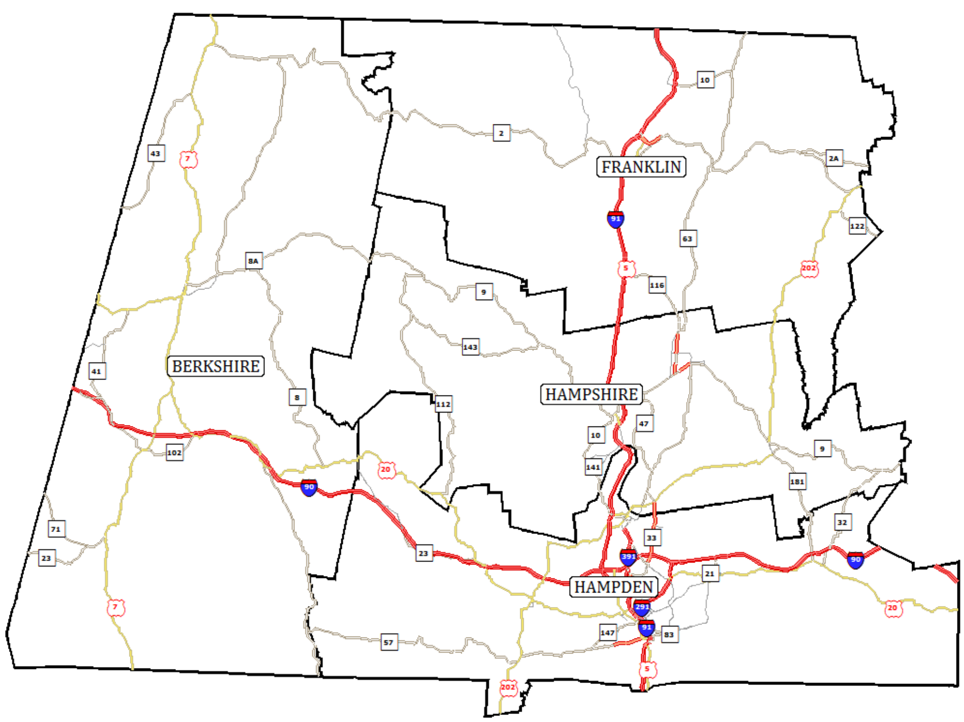

Figure 4 Major road network in the four-county area.

CHAPTER 4

METHODOLOGY

Three types of evacuations (a total of four case studies) are examined: a spill of a generic chemical along the highway, a dam failure or flood, and two mandatory hurricane evacuations. Each of the case studies has some similarities along with some distinct differences. These comparisons are shown Table 2. The chemical spill scenario assumes that the spill disables a small section of the roadway, and it assumes that people do not change their behavior in response to the spill: people still want to go to and from work, but simply take another route. The flood evacuation assumes that the roads are usable at the beginning of the incident, but as the flood progresses more links become disabled. This is same for the productions and attractions of the people that are located within the inundation zone or evacuation planning zone (EPZ).The hurricane evacuations assume that people completely change their thought processes and behaviors in response to the incoming threat. Since the evacuees are departing before the hurricane's high wind speeds and heavy rains enter the county, the roadway network is still intact. This assumption can easily be relaxed for the evaluation of other evacuation scenarios.

Table 2 Characteristics Examined Case Studies

	Chemical Spill	**Flood Evacuation**	**Hurricane Evacuation**
Scope	Local	Time varying	Wide
Behavior	Unaltered	Altered	Altered
Network	Links Disabled	Links Disabled	No Links Disabled

The characteristics of each of the three evacuations can be altered to be used in the other case studies. The disabled link aspect of the chemical spill or flood can be adopted by the hurricane evacuation. For instance, a bridge could be closed for maintenance in the days leading up to a hurricane or low laying roads could be flooded due to excessive rain. The modified behaviors can be adopted by the chemical spill if there needs to be an evacuation of the area surrounding the location of the spill. This type of scenario is where RMP*Comp (or a similar program) becomes a valuable tool. RMP*Comp estimates the radius that a chemical affects based on the specific nature and amount of the compound.

Loosely, these alterations can be attributed to the four-step transportation planning model. Trip generation corresponds to the behavior category; an altered behavior would be modeled as an altered set of productions and attractions. A portion of behavior also falls into trip distribution because a new coefficient (or a set of coefficients) for an evacuation-type trip is needed. The behavior could also affect mode-split, though only passenger vehicles are considered in this thesis. The altered network affects the traffic assignment portion of the model and in some cases alters some of the required intermediary steps of trip distribution.

One methodology does not suffice for all of the case studies since each study's scenario is different from the others. A more in-depth methodology is presented in the following scenario analysis sections. The scenario chapters can be read as independent chapters. Each scenario has its own results and conclusions for that specific scenario/evacuation; at the end the entire program and its ability to model the evacuations is examined. Items measuring the modeling aptitude include how well the program can accept the new and altered inputs to the planning model, how reasonable the results are, and the steps that the program has trouble easily completing.

CHAPTER 5

CASE STUDY I: CHEMICAL SPILL IN HAMPDEN COUNTY

(Work on this chapter has been in large part completed by Xuan Lu, M.S. UMass Amherst)

The chemical spill event takes place in Springfield, Massachusetts and the surrounding areas. Springfield is located in Hampden County, which is the southeastern most county shown in Figure 3. Because of the nature of the specific scenario, the trip generation and distribution steps are not altered from the regional county model. The main characteristic of the scenario is the disabling of select links of a main artery in Springfield. A chemical spill is a sudden, unexpected event; therefore, travel demand remains the same as a normal day; people still try to get back to their workplace or home. In this case study, the disaster is local enough that people do not need to vacate the area surrounding the event. This is not inherently true of all chemical spills; in some cases an evacuation of an area is necessary. The only option available for people to use is a passenger car; mode split is also not taken into account. Of the four steps in the transportation planning process, the only steps that are notably altered are the trip distribution step, where minor modifications to a time of day analysis are made, and the traffic assignment step, where DTA is used instead of the normally used STA. For this reason, no trip generation steps are included in the methodology.

5.1 Trip Distribution

The main parts of the trip distribution process are the calculation of the shortest-path matrix, obtaining the production-attraction (PA) matrices through, in this case, the use of the gravity model, and the transformation of the production-attraction matrices into origin-destination matrices. The shortest-path matrix is not altered from the regional model; therefore, it is not covered here. The production-attraction matrices that are normally used in the regional planning model are also used here.

5.1.1 Time of Day Analysis

The demand data provided by the PVPC modeled three trip types: HBW, HBNW, and NHB. The default distributions from the software (from NCHRP 187) provide unique trip distributions for each of the three trip types. Through talks with the planning agency, it was determined that the afternoon peak tends to have more traffic demand than the morning peak. In the NCHRP data, the morning peak is higher than the afternoon peak. Four percent of the morning peak (6-7 AM) is added to the afternoon peak (5-6 PM) to adjust the data. This caused the values to decrease from 19.2% (normal) to 15.2% (altered) in the morning and to increase from 13.7 (normal) to 17.7 (altered). The change in the distributions of the trips is shown in Figure 5. This figure shows the total trips made during a given hour. It includes both HBW trips that are departing as well as returning. The rest of the hours of the day remained unchanged. The other types of trips (HBNW and NHB) are also left unchanged. If more information existed regarding the trip distributions of the surrounding area then a more accurate time of day table could be constructed and used for analysis or modeling. These distributions are used to change the production-attraction matrices into hourly origin-destination matrices for use in the traffic assignment step. Each hour of the hours of the origin-destination matrices is summed across the three trip types in order to obtain the twenty-four hourly origin-destination matrices.

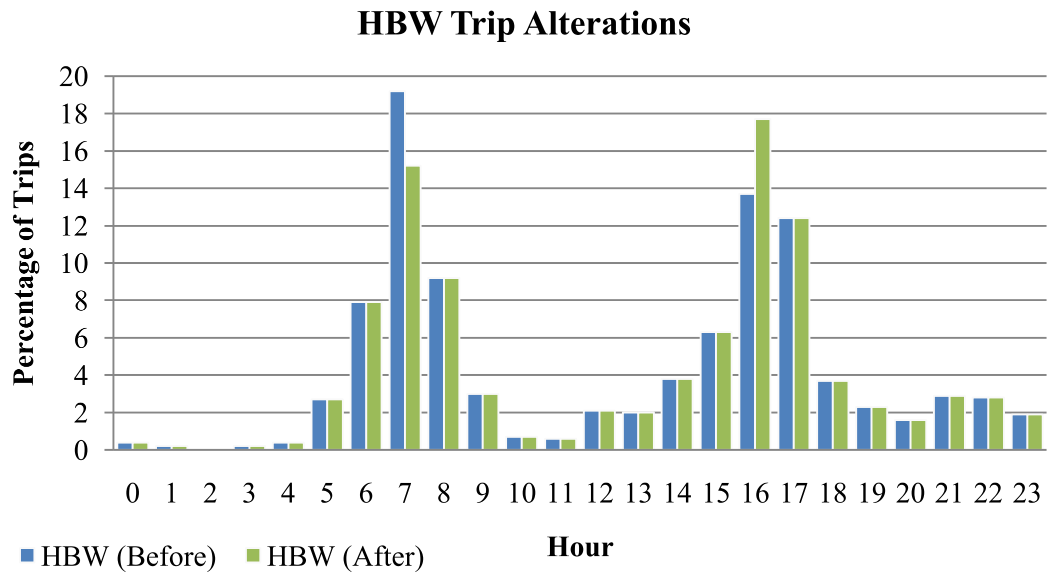

Figure 5 HBW Trip alterations due to local input.

In order to prepare this data for the DTA process these hourly demand matrices are divided into six ten-minute demand matrices. Again, if sub-hourly demand distributions are available that gave the demand in fine increments this would be preferred to the approximation made here.

5.2 Traffic Assignment

Traffic assignment is completed with the DTA module included with TransCAD. The analysis is applied to both the base case (or normal day) and the incident case (the chemical spill). In the base case scenario, no changes to the network are made; the network has all of its links activated. The incident case disables a large stretch of a major corridor in Springfield.

A static traffic assignment model considers that the traffic conditions over the course of the study period are stable or steady state. The study period is generally taken as a single hour, a period of several hours (morning or afternoon peak), or an entire day.

Results obtained from the assignment can be viewed as averages over the course of the entire period. Sometimes the assumption that the demand is uniform across the study period may not be valid; it has been seen that the travel times decrease at the front edge of a peak period and decrease on the outer edge of a peak period (Caliper Corporation 2007). The DTA module used in TransCAD can accommodate incidents that occur on the road during a given hour. The incident can decrease the capacity of a set of links (or a single link) by a factor that ranges from 0% (no effect on the links) to 100% (completely closed off). The algorithm in TransCAD is based on work completed in Janson and Robles with some additional modules and extensions that were created by Caliper (Janson and Robles 1995). DTA module uses First-In-First-Out (FIFO) flows to improve the accuracy of the simulation (Caliper Corporation 2007).

The assignment is run using an artificially more congested travel time than is actually present on the network. A ten-minute origin-demand matrix is multiplied by a factor larger than one (twelve in this case). This helps the DTA algorithm converge by using a reasonable initial condition. If nothing else is specified the algorithm uses free-flow travel times that may be significantly different from the congested travel times that are on the network during the period.

5.3 General Results

The scenario tested is located in Springfield, Massachusetts. The data file obtained from the PVPC contained 450 internal TAZs and 62 external TAZs. The PVPC provided four different years of data: 2000, 2010, 2020, and 2025. The data from the 2000 U.S. Census is used for the demand calculations. The segment of the road chosen is a major artery that if disabled would cause severe impediments to and from Connecticut, New York City, Western Massachusetts, and the Massachusetts Turnpike. The area also contains a curve on Interstate 91 that is notoriously known as the “Chicopee Curve”, where there have been numerous incidents concerning overturned trucks.

The spill occurs during the evening peak on Interstate 91 from Exit 10 to Exit 12, covering about two miles of closed roadway. A map of the region along with the closed segment is shown in Figure 6. The road closure would block access from downtown Springfield to the Massachusetts Turnpike (Interstate 90), and to the northern portions of the region. A truck crashes at 4:00PM. The truck is assumed to be carrying a caustic chemical and disables a section of road from 4:00 PM until 7:00 PM. The total analysis period lasts for seven hours from 3:00 PM until 10:00 PM.

There is still access for people to use Interstate 291 to the east, and for people to head from Interstate 391 to Interstate 91. Access points to the Massachusetts Turnpike (Interstate 90) are shown with circles in Figure 6. The general expectation is that people heading westbound would use Interstate 291, and people heading eastbound or northbound would divert to Route 5.

Figure 7 shows a flowmap of the region. The color of the line denotes the volume over capacity ratio (V/C). Red lines V/C’s are high, and green lines show low V/C ratios. Thick lines denote high volumes, and no or thin lines show very low volumes. This is followed in each chapter; if this convention is not followed, it is noted.

There are four main areas that are severly, adversely affected from the spill. These areas are eastbound Park Street, Memorial Rotary, the ramp from W. Columbus Avenue to the Route 5 Bridge, and Columbus Avenue at the entrance to Interstate 91. The relevant characteristics about these intersections are shown in Table 3. The numbers in the first column relate to the locations denoted in Figure 7.

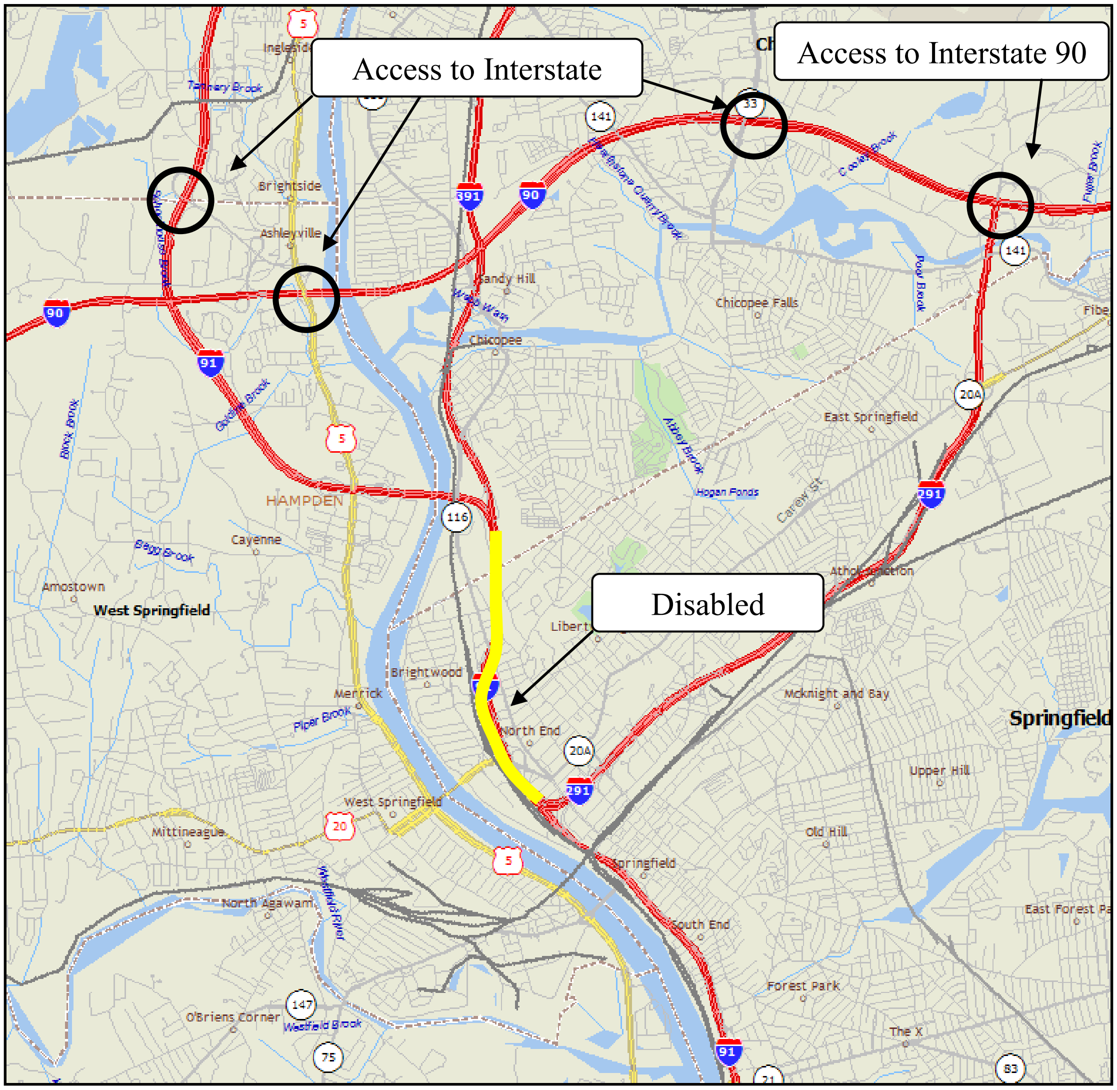

Figure 6 Springfield with disabled links labeled.

Figure 7 Change in the congestion from a normal day to the chemical spill.

Table 3 Areas with a Significant Change in V/C Ratio

Location	**Incident Case** Average Traffic Flow (veh/ln/hr)	V/C Ratio	**Base Case** Average Traffic Flow (veh/ln/hr)	V/C Ratio
1. EB Park Street	936	1.47	607	0.96
2. Memorial Rotary	1,352	1.57	1,199	1.39
3. Columbus Avenue at Interstate 91	1,103	1.73	672	1.06
4. Ramp to Route 5 (S. End Bridge)	1,076	1.91	1,003	1.78

The differences between two of the main traveled routes are shown in Figure 8. These two segments are parallel to each other. People that have been diverted off of Interstate 91 are likely to take Route 5 as an alternative. It should be noted that the rest of the vehicles spread themselves through other roads in the network. It is not expected that all of the vehicles diverted from Interstate 91 would take Route 5. This explains why Route 5 does not spike up to take on the volume of the vehicles that would usually use Interstate 91.

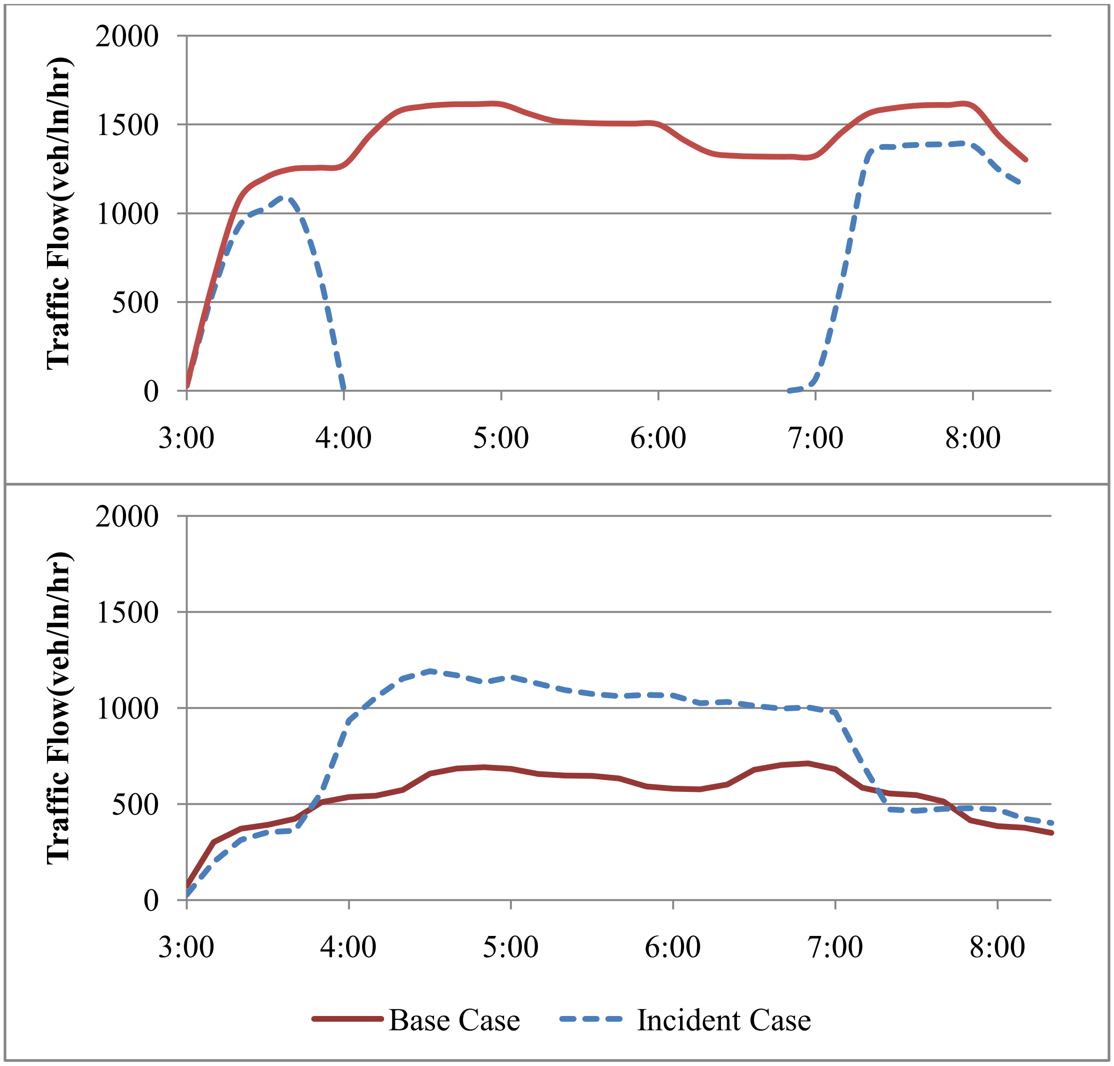

Figure 8 Base Case and Incident Case for Interstate 91 (Top) and Route 5 (Bottom).

5.4 Lessons Learned

There are several important lessons that were learned in the process:

- In order to obtain accurate results, the initial conditions of the network must be taken into account. To create acceptable results in this study, a static, ten-minute traffic assignment matrix was multiplied by a factor greater than one (in this case a factor of twelve) and was used as the initial conditions by “warm starting” it into the dynamic traffic assignment matrix.

- The warm up period (or the period before the incident occurs) must be sufficiently long to allow traffic to get up to normal levels before the incident.
- The time after the incident must also be sufficiently long. This allows for determining the plausibility of the results, and it also allows for the analysis of how well the network recovers after the event. The traffic on the disabled links may be low for a significant amount of time after the road has reopened. If this occurs, the post-incident period should be extended.
- Uncongested periods should not be excessively long. If the analysis were run from a very empty state the results may be less valid. The DTA algorithm can easily converge with light traffic because only one measure of convergence is used for all of the periods. These uncongested periods can overshadow the congested periods.
- The time resolution in this study (ten minutes) gives adequate results. Five- and fifteen- minute increments can also be tried.

CHAPTER 6

CASE STUDY II: FLOOD EVACUATION IN FRANKLIN COUNTY

(Work on this chapter has been in part completed by Haizhong Wang, M.S. UMass Amherst)

The flood evacuation contains characteristics from the other case studies. The network is changing over time like in the chemical spill scenario, and the behavior of the people is changing similar to the hurricane evacuation. A major difference is that both of these characteristics are changing over time. As the flood progresses temporally, more roads are disabled and more people are evacuating.

The four-step model is used here to model a flood in Franklin County. It should also be noted that throughout this case study GIS tools are used to determine the area of each TAZ that is contained by the evacuation planning zone (EPZ) and to edit the network.

6.1 Trip Generation

In the flood scenario, as time passes, more and more people must be evacuated. The people in the affected area alter their behavior from heading to work to heading to a shelter. People living in the inundation zone or the EPZ need to be evacuated. This requires a new method to generate the productions and attractions for each TAZ. A basic pictorial description of the various types of zones is shown in Figure 9. Each zone is closer to the approaching threat than the last zone. The EPZ is the closest zone, and is most vulnerable to the threat. The other protective action zone (PAZ) and precautionary zone (PZ) are less at risk than the EPZ.

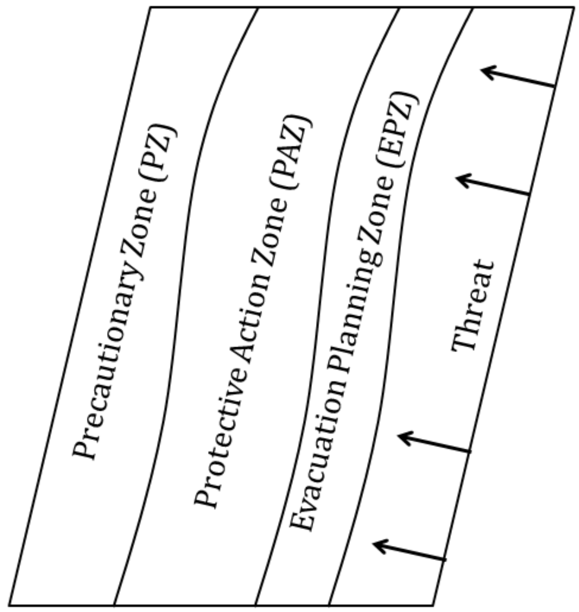

Figure 9 Different types of emergency planning zones

Because the flood will most likely destroy everything, it is posited that people take all of the cars they possibly can. There are also people that may be working inside the EPZ who must also evacuate. Other factors can also be included such as extra bus trips that must be made to get schoolchildren to safety. These factors are shown in the following equation:

$$P_i = B_i + \varepsilon * F_i * TE_i + \alpha * F_i * Auto_i \quad (1)$$

Where:

P_i = Productions of TAZ i

B_i = number of extra buses needed in TAZ i

ε = employment factor

F_i = % of TAZ i that is flooded

TE_i = total employment of TAZ i

α = auto factor

$\mathrm{Auto_i} = \text{number of autos in TAZ i}$

This formula assumes that the homes and offices of the people living and working in the area are evenly distributed across the area. The factors may be used to sway this assumption if there is reason to believe that people tend to congregate nearer to the water.

These evacuees must go somewhere. The attractions are made using the following formula:

$$A_i = S_i + \rho_i * (1 - F_i) * HH_i \qquad (2)$$

Where:

$A_i = \text{Attractions of TAZ i}$

$S_i = \text{Shelter space in vehicles per shelter}$

$\rho_i = \text{friends and family factor}$

$HH_i = \text{number of households in TAZ i}$

This formula implicitly assumes that each household that takes in a family only takes in one vehicle per family. The attractions are balanced to the productions implying that people squeeze into shelters or their family and friends' houses if they must. This also ensures no extra evacuation trips are created because of excess shelter space.

The existing productions and attractions that are found in the regional planning model provided by the FRCOG must also be changed. The old productions and attractions did not consider than some percentage of the TAZs would be underwater. The productions and attractions are reduced by the percentage of the TAZ that is within the EPZ, and then rebalanced to the new productions. These trips are replaced by the trips from above. In other words, if twenty percent of a TAZ is flooded and normally there are one-hundred trips made, now only eighty trips are made plus some evacuation trips.

This becomes more complicated when the time variance is considered. The places that have already evacuated do not evacuate in each period. The process of calculating the evacuation productions and attractions and the recalculation of all of the original productions and attractions must be completed for each analysis period. Each TAZ in the EPZ is marked with the period that the evacuation takes place. In the first period, the first section may be evacuated. Then in the second period, the first period does not have any evacuation trips, but the second section will, and so on until the analysis is completed. The recalculated original productions and attractions are kept for each period since the area remains flooded in the next period.

6.2 Trip Distribution

Similar to the calculations of the productions and attractions for each period, the distribution must also be completed for each period separately.

6.2.1 Shortest-path

The shortest-paths are different for each of the periods depending on how far the flood has reached and what roads have become unusable. In some cases certain sections of the network may become isolated if only roads that have a functional classification greater than one (or non-local roads) are used. This varies network to network. It is advisable to turn on selected local roads to model these. This may require obtaining data on links that are not normally modeled. When the network starts becoming bifurcated, the people may not be able to get to the other side of the region without first leaving the county. It is still possible to get to the other side of the region, but they would have to leave the county and then re-enter the county at another point. The original regional planning model is not built to handle this movement.

Virtual links are added to connect the two sides of the network to emulate people leaving from one portion of the county and reentering in another part. These links' characteristics are estimated using a plausible path that someone might take to get around the flooded river along with another mapping program (Google Maps). These virtual links help the assignment algorithm attain convergence.

6.2.2 Obtaining the Production-Attraction Matrices

Using the productions and attractions from an earlier step, the trips from each TAZ to each of the other TAZs can be obtained. The gravity model is used to model this. The form of the gravity model is covered in the hurricane evacuation section. Each period is modeled independently from the other periods.

6.2.3 Time of Day Analysis

The time of day analysis step should be completed for each of the periods. A new column denoting when each of the evacuations takes place is added to the time of day table. In some cases (depending on the average trip length), the granularity of time needs to be coarsened. If this is the case, the time of day chart may need to be collapsed from the original single-hour NCHRP time of day chart into a two-hourly time of day chart. After each hour and each trip type is run through the time of day process, the external-to-external trips (generally already in the form of an origin-destination matrix) can be added back in using the time of day analysis.

6.3 Traffic Assignment

The traffic assignment is modeled statically in this case. This is different from the previous modeling activity. The DTA module of TransCAD is built to accept an incident. That is, a singular incident. The software cannot currently handle multiple incidents or road closures. Because the network eventually becomes segmented, in order to maintain accuracy in the STA, the periods are taken in two-hour blocks instead of the normal one-hour block. This allowed most of the trips that began in one period to finish their trip by the end of the period. This would not be an issue in the DTA where the program keeps track of where vehicles are on the network.

6.4 Modeling Process / Results

The scenario examined in this chapter is an instantaneous dam flood in Franklin County, Massachusetts. The flood is the probable maximum flood (PMF), which is the worst flood that is reasonably expected to occur. This takes into account both weather and hydrologic conditions at the time of the failure. An inundation map and corresponding GIS files were obtained from the FRCOG representatives that denote the inundation area in the event of the PMF. By the request of the county representatives, the following disclaimers should be noted: "*The inundated areas shown on these maps reflect an event of an extremely remote nature. These results are not in any way intended to reflect upon the integrity of the Deerfield River Project. Depicted boundaries are approximate; these shapefiles are intended only for planning use only, and are not intended for survey or engineering use."* These notes are found on the original maps or are explicitly noted in communications with the representatives.

According to the projected data for 2003 obtained from the FRCOG, there was a population of about 72,000, about 28,000 homes, and 47,000 vehicles. There are sixty-seven internal TAZs and forty-one external TAZs. The region is split by the Deerfield and Connecticut Rivers. The Deerfield Dam is about twenty miles to the northwest of the

Greenfield, Massachusetts in Vermont. The Harriman Dam holds back the water of the Harriman Reservoir.

In this case study, the dam breaks at 10 AM, though there is enough warning so that the people living nearest to the dam have time to evacuate. The evacuation takes place in four steps starting at 8 AM and moving in two-hour increments from then. The sections that are evacuated and the links that are disabled are shown in Table 4. The inundation area is shown in Figure 10. There is a five-hundred foot EPZ that surrounds this area. The distance that the flood has traveled down the river is denoted with red lines. The times are relative to the time of the dam failure. The sections are labeled based on two-hour blocks. That is, a section is defined by how far the water has traveled in two hours starting from the time the dam breaks.

Table 4 The Characteristics of Each Period

Period	Evacuation Section	Roads Disabled
08:00 – 10:00	Section I	None
10:00 – 12:00	Section II	Section I
12:00 – 14:00	Section III	Section I and II
14:00 – 16:00	Not Modeled	Section I, II, and III

These next several sections outline important results from each of the steps that are presented in the last sections.

6.4.1 Trip Generation

One of the first items needed for the trip generation process is the percent of each TAZ within the EPZ. This is obtained using the geographic utilities toolbox within TransCAD. The percentage of each TAZ within the EPZ is shown in Table 5.

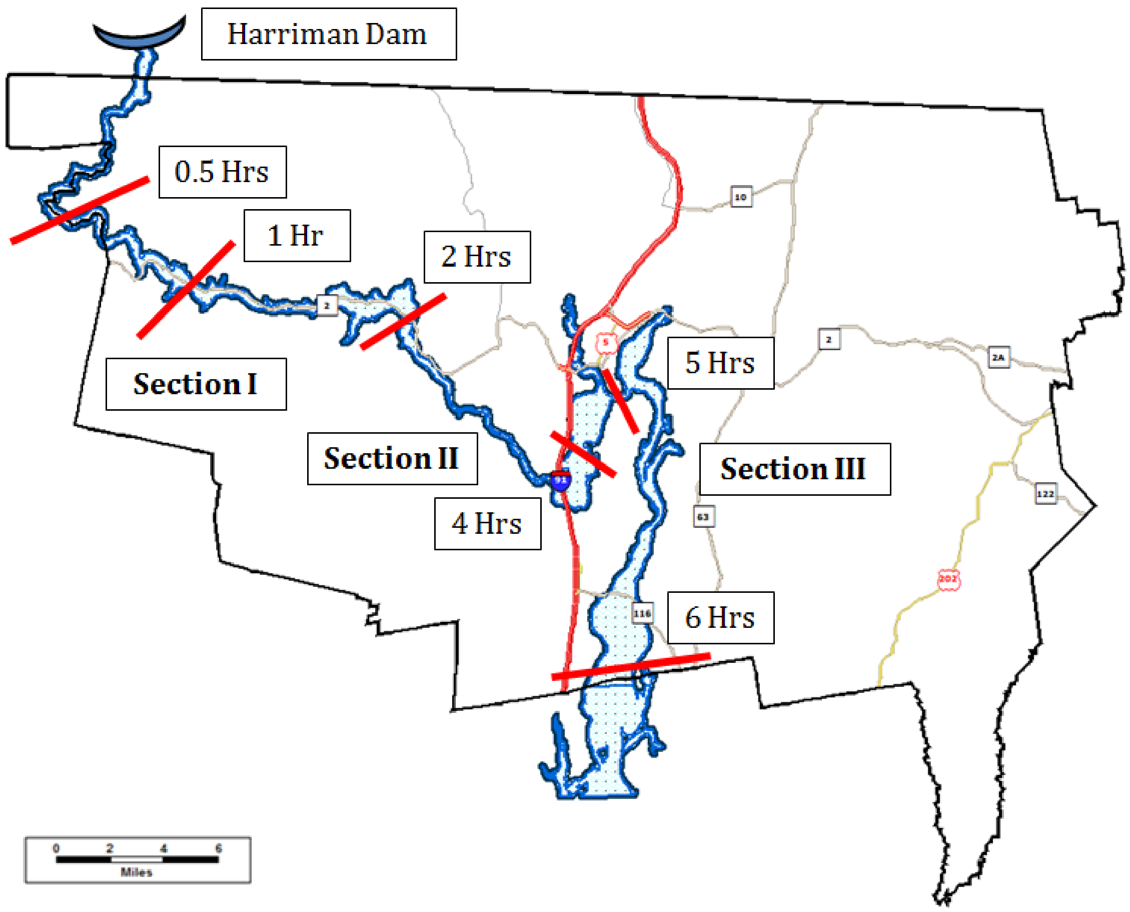

Figure 10 Harriman Dam inundation area along with times and section numbers.

Table 5 Percentage of the TAZ within the EPZ

TAZ ID	% in EPZ	TAZ ID	% in EPZ	TAZ ID	% in EPZ
1	8%	**29**	67%	**49**	95%
2	20%	**30**	38%	**50**	58%
3	9%	**31**	12%	**51**	52%
5	12%	**33**	48%	**53**	11%
10	5%	**38**	82%	**54**	9%
11	18%	**40**	12%	**65**	26%
12	39%	**41**	**100%**	**66**	**100%**
25	5%	**42**	6%	**67**	52%
27	2%	**44**	11%		
28	2%	**48**	14%		

Two of the TAZs, shown in bold in Table 13, are completely inundated, and they must be fully evacuated. These percentages are used with the production equation to determine how many vehicles evacuate for a particular TAZ. The table below outlines the number of productions for each period/section.

Table 6 Evacuation Productions for Each Period

Period	Evacuation Section	Productions
8:00 – 10:00	Section I	1,257
10:00 – 12:00	Section II	843
12:00 – 14:00	Section III	8,075
14:00 – 16:00	Not Modeled	0
Total	--	10,975

The flood reaches Greenfield between 12-2 PM. This explains the large spike in productions during the evacuation of Section III.

Shelter data was obtained from the FRCOG. This data supplied enough information to create the attractions for each zone. There are over one-hundred shelters in the area with a combined maximum capacity of over sixty-thousand people. The shelters include schools, religious institutions, city halls, and hotels. The characteristics of the shelters vary widely: some have food, water, and beds for people, while others have only food and water. Some of these shelters are in the inundation zone and therefore are not available for the evacuation. The total capacity lost due to flooding is about 10,000 spaces. Regardless, there is a satisfactory amount of shelter space for the eleven-thousand people that may be evacuating. The attraction equation is used to obtain the attraction information for each TAZ and each period.

6.4.2 Trip Distribution

The shortest-path matrix is calculated for each of the periods. Local roads are turned on by selecting certain roadway segments that people might have to use if the flood disables the primary road network. This is completed through visual inspection along with satellite imagery to ensure only traversable roads are chosen. The smallest modeled road's attributes are attached to these roads. During the completion of this process in TransCAD, the areas that are cut-off or isolated as a result of the flood can be discovered. The shortest-path results report that certain TAZs could not be connected. In almost all of the cases there is a route that connected the area to other TAZs, but it is a local road and not included for analysis in the regional model. One TAZ (the citizens of Deerfield and East Deerfield) is completely cut off without any roads out if a flood of this magnitude occurs. The people may be able to drive around the flood, but the data does not provide enough information to determine the elevation of the flood at every point. The virtual links are also added at several points to emulate people going outside of the county and then back into the county on the other side of the flood. The travel times are estimated using another mapping program, and the capacities are set to a high value to let people use the virtual links freely. Neither the virtual links nor the local roads are on the shortest-path when the flood has not disabled any links.

The FRCOG uses a friction-factor lookup table for their modeling. The table must be altered to accommodate the larger travel times that are now present on the network. The last row of the table is extended to allow very long trips to have a low value for their friction-factors.

6.4.3 Traffic Assignment

Each period is modeled independently from the other hours. This captures the progressive, dynamic nature of the flood. STA is used with the BPR volume delay function. The BPR function is described in the hurricane evacuation case study. The values for the α term in the BPR function ranged from 0.15 to 2.0 for the FRCOG data.

New two-hour capacities are generated for all of the links on the network in order to match the lengths of the study periods.

6.5 General Results

The results vary widely depending on what period is observed. There is not a significant amount of traffic on the roads until Section III is evacuated. The first period (8-10AM) does not suffer much congestion. The highest V/C ratio is 0.89, which is still acceptable. The maximum flow in one direction is 1,804 vehicles in two hours. The second period (10-12PM) is also not very congested. The maximum V/C ratio is only 0.72 which is less than the previous time; the maximum flow is 1,190 vehicles in two hours. The next period (12-2PM) is more interesting than the previous two. The flood has now cut off the main bridge (Interstate 91) connecting Greenfield and Springfield. It has also cut off two of the on- and off- ramps that connect Route 2 with Interstate 91 outside of Greenfield. In addition to having notable links cutoffs there are over eight thousand vehicles evacuating. Two links have V/C ratios of 2.96, but most of the V/C ratios fall underneath 1.59. The maximum flow on a link is 2,665 vehicles in two hours; most are underneath 1,980 vehicles per two hours. This period is shown in Figure 11.

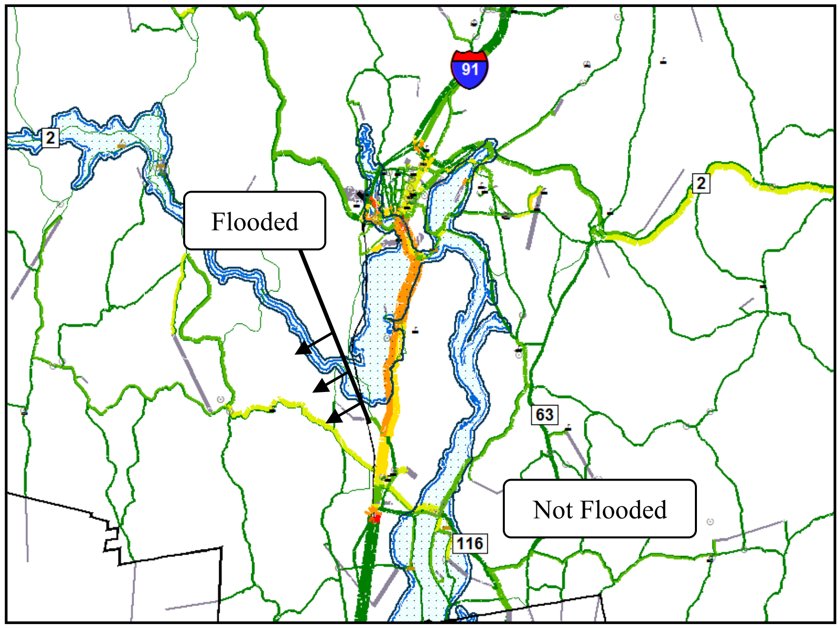

Figure 11 Flow map of 12-2 PM.

The final modeled period is from 2-4 PM. No one in Franklin County is evacuating anymore; people in Hampshire County to the south should be evacuating, but this area is outside of the study area. This period shows what the network is like after all the people that need to evacuate have evacuated. All of the roads that allow people to cross the river are underwater and disabled. The people now have to go around the flood by driving to the south or west. People are now using Route 63 instead of Interstate 91. Route 63 runs parallel to Interstate 91 but is on the opposite side of the Connecticut River. This is shown in Figure 12. People must also drive a considerable distance to the north to get into or out of Greenfield. Normally, people would use either Route 2 or Interstate 91 to access Greenfield, but now the shortest-path is Route 10 to the north. This is shown in Figure 13.

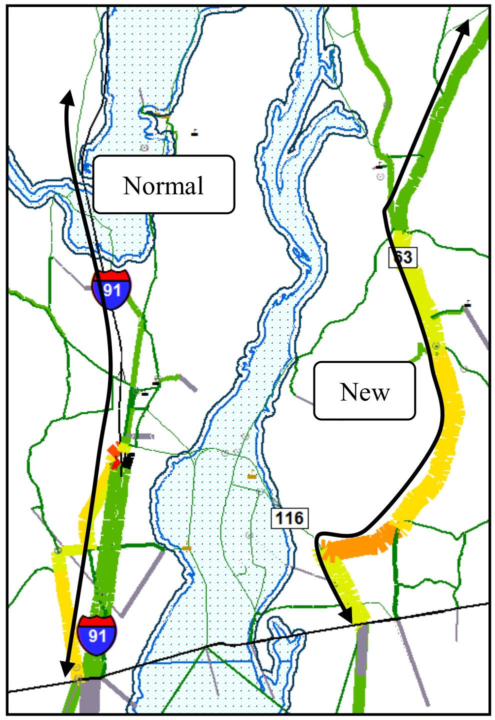

Figure 12 Flow map of 2-4 PM – Interstate 91 diversion route.

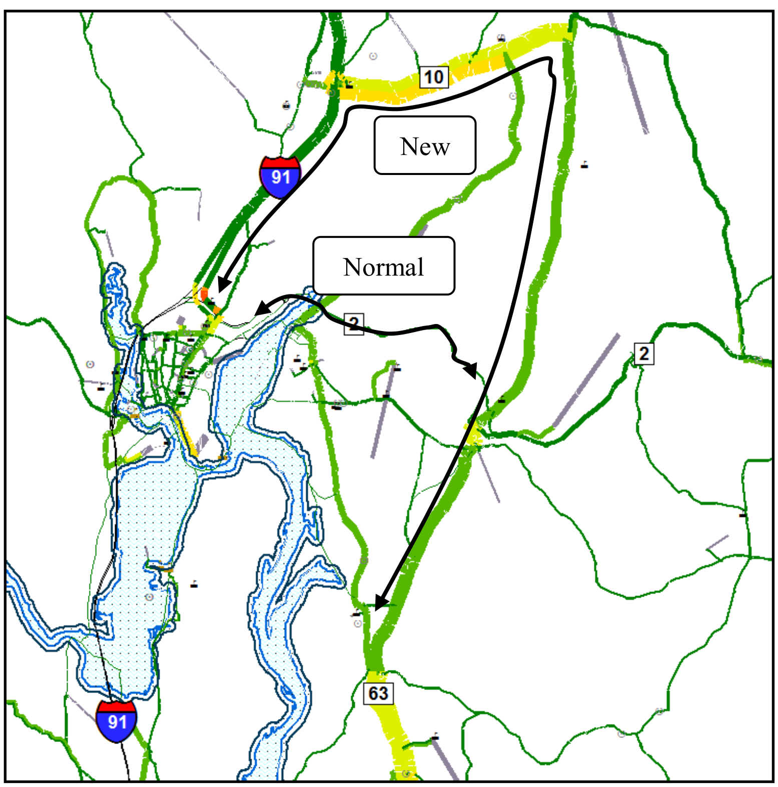

Figure 13 Flow map of 2-4 PM – entering and exiting from Greenfield.

6.6 Lessons Learned

Some lessons were learned in the process of modeling the flood:

- An accurate understanding of the nature of a dam failure flood evacuation and its difference when compared to a hurricane evacuation or a chemical spill on a segment of highway is very important in determining the evacuation strategy.
- A staged evacuation strategy defined by a two-hour time block is suitable to the dam failure flood evacuation and generated reasonable results. The two-hour time block is determined by taking the longest trip time into consideration. An excessively short period will miss some trips while an excessively long period will make the results less accurate.
- To make the algorithm converge, some virtual links need to be created by connecting some of the TAZs. In this way, those who want to take a long trip to the other side of inundation area can find a way. However, in the actual runs of some of the periods, there are no vehicles using these virtual links for evacuation. Towards the end of the study period these links are used.
- The staged evacuation strategy assumes that those who are not asked to evacuate in the downstream of inundation area will take trips as if it were a normal day. This approach does not model those people who evacuate earlier than scheduled.

CHAPTER 7

CASE STUDY III: HURRICANE EVACUATION IN BERKSHIRE COUNTY

The first hurricane evacuation scenario takes place in Berkshire County. This county is shown in Figure 3. A discussion of how the four steps of the transportation planning model (excluding mode split) are modified is found in the next several sections. Following the methodology laid out in those sections, a results section is presented that outlines specific results of the model.

7.1 Trip Generation

The first and most notable change to the regional model is the adjustment of the productions and attractions of the evacuees. In a normal day, people are making a wide variety of trips such as from home to work, work to the store, home to the store, and so on. During a hurricane, the productions are peoples' homes, while the attractions are cities outside of the hurricane's path or possibly shelters inside the county (depending on the hurricane severity and the facilities available in the county). In order to replicate the trip decision process a production model using basic available data is created.

Several assumptions are required to create this model. The first assumption is that families would like to fit in the fewest number of vehicles as possible in order to keep their family unit together. This is different from the flood case study, in that the fate of the property is much less certain. Secondly, if the number of cars required is greater than the available cars then the families squeeze in and take all of the vehicles in the TAZ. The third assumption made is that every household makes at least one trip. This implies that the evacuation rate across the entire population is 100% (that is, every resident must evacuate). The final assumption made is that there is, on average, four seats per vehicle. This method is shown below:

$$T_i = \min\left(\text{ceiling}\left[\frac{\text{HH Size}_i}{V_{Veh}}\right], \frac{\text{auto}_i}{\text{HH}_i}\right) \tag{3}$$

Where:

$\text{HH}_i = \text{Households in TAZ i}$

$\text{HH Size}_i = \text{average number of residents per HH in TAZ i}$

$V_{veh} = \text{average number of seats in a vehicle}$

$\text{auto}_i/\text{HH}_i = \text{average number of vehicles per HH in TAZ i}$

$T_i = \text{Number of trips producted for each HH in TAZ i}$

In order to ensure that each household makes at least one trip, the minimum number of trips must be greater than one trip per household or,

$$T_i \geq 1.0 \tag{4}$$

The final number of productions made for each TAZ is obtained by multiplying the number of households by the production rate and the participation rate:

$$P_i = \phi_i * \text{HH}_i * T_i \tag{5}$$

Where:

$\phi_i = \text{Participation rate of TAZ i}$

This model can represent multiple areas of departure such as the evacuation planning zone (EPZ), the protective action zone (PAZ), and the precautionary zone (PZ). These regions are shown in Figure 9 in the Flooding chapter. In the areas that are farther away (PAZ and PZ) from the path of danger less people are likely to evacuate. This method accounts for this by multiplying the production of each TAZ by the expected percentage of participating citizens. This document takes the ϕ value to be equal to 1.0. If more areas are established the ϕ value can vary depending on each zone (for example, ϕ = 1.0 in the EPZ, ϕ = 0.75 in the PAZ, and so on).

While it is obvious where the trips originate from, where people are attracted to during a hurricane is more difficult to determine. If shelters are open and available then certainly people are able to go to these locations. In the absence of shelters, the evacuees are able to use hotels or friends and relatives homes. If this information is available, or if the in-county locations are full or unavailable, then another method other that what is presented here is needed to determine where all of the excess trips go to seek shelter.

To model excess trips leaving the county, the model assumes people use the external TAZs during an evacuation in the same proportion they have been using them under normal conditions. This is shown below.

$$A_{i,evac} = P_{tot} * \frac{A_{i,norm}}{\sum_{i=1}^{n} A_{i,norm}} \tag{6}$$

Where:

$A_{i,evac} = \text{Total attractions fot TAZ i}$

$A_{i,norm} = \text{Total of HBW, HBNW, NHB trips for TAZ i}$

$P_{tot} = \text{Total productions leaving the county}$

If the planning agency has data on how much shelter space there is then these shelters can be taken out first, and the remaining trips can follow the attraction formula or replace P_{tot} with $P_{tot} - \text{Trips to internal zones}$. The trips to internal zones are equal to the shelter space divided by the occupancy rate of the vehicles.

7.2 Trip Distribution

The trip distribution process has three main steps: finding the shortest free-flow path between all of the centroids to all of the other centroids, obtaining the production-attraction matrices, and converting the production-attraction matrices into origin-destination matrices. The first two parts are left unaltered in this methodology. One of the sub-parts during the conversion process is changed to reflect the different timing during the evacuation.

7.2.1 Shortest-path

Using the network of roads with a functional classification greater than zero (or all of the non-local roads), the shortest-paths between all of the centroids to all of the other centroids, based on free flow speeds, are calculated. This is not altered from the normal regional model; as such, it is not covered in the results section.

7.2.2 Obtaining the Production-Attraction Matrices

The number of trips produced and attracted by and to each zone is reviewed in a previous section. Using these values along with the travel times estimated from the previous step, the production-attraction matrices are obtained by implementing the gravity model. The gravity model is commonly used in transportation planning. This model takes the form of:

$$T_{ij} = \frac{P_i * A_j * f(C_{ij})}{\sum_{j=1}^{n} A_j * f(C_{ij})} \quad (7)$$

Where:

P_i = Productions of zone i

A_j = Attractions of zone j

C_{ij} = Travel cost from zone i to j (in this case free flow travel time)

$f(C_{ij})$ = Friction-factor from zone i to j as a function of C_{ij}

7.2.3 Time of Day Analysis

In the event of a hurricane, people can evacuate quickly or slowly. Building on this, people can take multiple days to leave their homes or they can take a single day to leave; a single day evacuation example is shown in Figure 2. This figure depicts three evacuation rates adapted from suggested planning values from the same series of reports mentioned earlier (HES 2003, AL HES 2001, MS HES 2001, HES 2000). Another important period to account for is the period when people are leaving their work places in response to the evacuation order. This is modeled by summing all of the trips that have already made it to work and sending these people home in the hours following the evacuation order. The results from this section are used in the production-attraction to origin-destination (PA→OD) conversion process.

The slower evacuation means people evacuate over a longer period of time; for each hour the slow evacuation releases less people than the medium and fast speeds. The fast speed finishes first, but it releases more people for each hour. Each of these evacuation speeds implies the perception of the danger of the hurricane. For example, the slow evacuation rate may be the appropriate model for a weaker hurricane (Category 1), while the fast speed could be representative of a strong hurricane (Category 4 or 5). It is assumed that one-hundred percent of the population evacuate because the evacuation is a mandatory evacuation. This gives an estimate of the longest time for each evacuation speed because the maximum volume of people are leaving. In addition, it is important to note that according to the studies in all of the situations examined some people tend to evacuate before the evacuation is ordered, but this value is not over twenty percent of the population (MS HES 2001). This group of people may be more cautious or dislike congestion more than the rest of the population.

7.3 Traffic Assignment

The final step is to run the traffic assignment algorithm. Normally, planners use a static traffic assignment (STA) procedure. However, here a dynamic traffic assignment (DTA) procedure is used to model the evacuation. STA treats the demands and capacities of the network as fixed and constant over the course of a day or several hours. Another implication in a static traffic assignment is that vehicles finish their trips within the period they are generated. DTA allows the demands and capacities to be variable and non-fixed values over the course of the day. This allows trips that are longer than the assignment period to be made successfully. That is, DTA tracks a vehicle through multiple time segments if the trip length is longer than the length of the period. The data required is nearly identical to the data needed for the static assignment algorithm. The function used in the DTA is the deterministic user equilibrium method. This closely follows Wardrop's first principle that states, "The journey times in all routes actually used are equal and less than those which would be experienced by a single vehicle on any unused route. Each user non-cooperatively seeks to minimize their (ed.) cost of transportation" (Wardrop 1952). The Bureau of Public Roads (BPR) function is used in for the volume delay function (VDF) (Bureau of Public Roads 1964). The BPR function takes the form of:

$$t(v_i)_{BPR} = t_{f,i} * \left(1 + \left(\frac{v_i}{c_i}\right)^{\alpha}\right) \tag{8}$$

Where:

$t_{f,i}$ = free flow travel time on link i

v_i = volume on link i

c_i = capacity of link i

α_i = parameter

This function determines how the travel time on the links changes as the volume approaches (or surpasses) the capacities of the links. α takes a different value for each link depending on its individual characteristics. Spillbacks are required for DTA, but they are not required for STA. Spillbacks occur when the amount of vehicles trying to use a link is greater than the physical space available on the link. The amount of space available on a link is known in TransCAD as a link's storage capacity. A recommended value is two-hundred and ten vehicles per lane per mile of roadway (Caliper Corporation 2007).

7.4 Modeling Process / Results

This scenario occurs in Berkshire County, MA. A hurricane would certainly affect many more areas than just Berkshire County, but this model only looks at the effects on the one county. The BRPC supplied a complete regional model including 143 internal zones and 37 external zones (for 180 total zones). The population of the county according to the data in the model is about 135,000. There are about 56,000 households, with an average household size across the county of 2.4. Berkshire County is bounded by Franklin, Hampden, and Hampshire Counties to the east, Vermont to the north, New York to the west, and Connecticut to the south.

The modeled scenario is a mandatory (100%) evacuation beginning at 10 A.M. on a workday. The projected path of the hurricane forces everyone to head to the west, as the hurricane may head to the east. No external trips are factored into the model during this analysis. Trips may be coming from other counties as well through this county. This is examined in the many-county regional hurricane model examined in Chapter 8.

7.4.1 Trip Generation

Several reports published by FEMA and the U.S. Army Corps of Engineers give some values to compare the trips produced using this method with values that are recommended for planning or that have been estimated from past hurricanes (HES 2003). The results from the production model presented earlier are on a TAZ basis; in other words, each TAZ has its own production rate. After each TAZ's productions are calculated, the total number of evacuation trips are summarized by dividing the total number of trips made by the total number of households and by comparing the number of trips against the total number of vehicles. In this way, summary statistics are calculated to compare with the values provided by several of the previously noted reports. These findings are shown in Table 7.

Table 7 Productions by Vehicle Trips per HH (Left) and Percent of Vehicles (Right)

Area	Rate	Area	Rate
Alabama	1.16-1.36	Apalachee Bay (FL)	65-75%
Apalachee Bay (FL)	1.20-1.30	NW Florida (FL)	65-75%
NW Florida (FL)	1.16-1.36	Tampa Bay (FL)	65-75%
Mississippi	1.15-1.49	Georgia	65-75%
		New York	70%
		North Carolina	60-70%
		South Carolina	65-75%
Berkshire County	**1.01**	**Berkshire County**	**66%**

The summary statistics for the BRPC data and the production model suggest that the number of trips may be underestimated. The percentage of trips taken per household is lower than the other reports, but the percentage of vehicles used in the evacuation is within the lower limits of all of the reports which give a range. The value obtained is largely dependent on the average occupancy of a vehicle. In this study, the value is assumed to be four seats per vehicle. The rates are insensitive after an available seating capacity of roughly three seats per vehicle (that is, the number of trips generated is very large with an occupancy of one seat and the extra trips generated quickly stabilizes after three seats per vehicle). If the expected average occupancy is much lower than three seats per vehicle, the procedure should be repeated.

The attraction exit points are taken be the western border exits. These exits are highlighted with circles in Figure 14. In response to advice from the regional planning agency, the attraction formula is altered slightly to force the number of trips that would be taken to the southernmost two evacuation points to be 0.1%. The most used TAZ is US 7 to the north. This route takes 23.5% of the trips, while the next most used routes are US 20 (16.2%), Rt. 295 (14.6%), and Rt. 23 (13.7%).

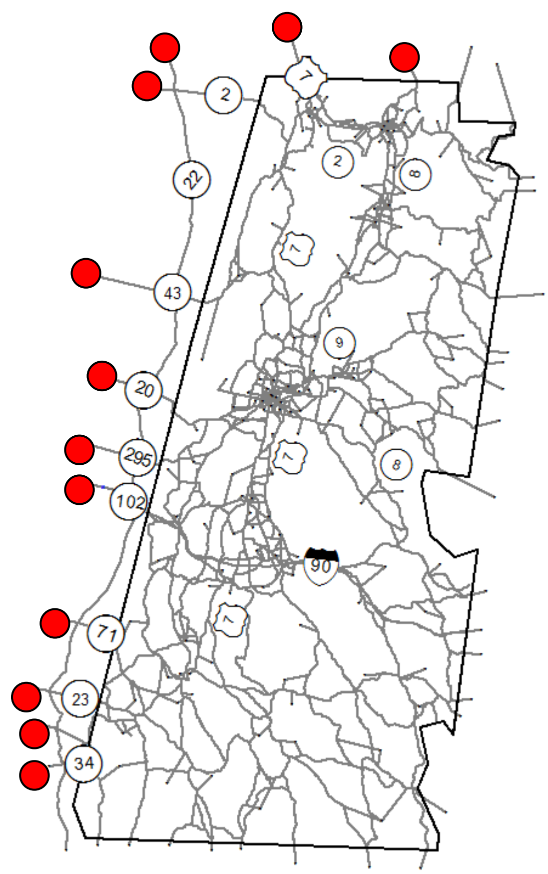

Figure 14 Evacuation attraction points.

7.4.2 Trip Distribution

Using the gravity model (Equation 5) with $f(C_{ij}) = \exp(-c * C_{ij})$, where c is a constant, a PA matrix for each of the four trip types is obtained. The friction factor relates to people's desires to make different length trips. For this model, *c* is taken to be 0.15, which is in-between the base model's HBW (c = 0.16), HBNW (c = 0.14), and NHB (c = 0.13) trip types. This value represents that the trip length distribution of these trips should be similar to the normal trips made in the base model. The normal-trip friction factors coefficients are left unchanged from the regional model.

After obtaining the results of the gravity model, the results are modified from twenty-four hour production-attraction matrices into twenty-four one-hour origin-destination matrices using the PA→OD tool in TransCAD. The hourly trip table is then modified to represent the shift in trip times.

It is important to take into account people leaving from their work who travel to their homes after the evacuation order is made. This is modeled by taking the time of day information from NCHRP 187 and manipulating the percentage of people arriving and departing during each hour (Sosslau, et al. 1978). The evacuating people that are at work before the time of the evacuation are sent back to their homes the hour that the evacuation order is made. The release of people at work to their homes could be spread out over several hours. This is modeled in TransCAD by adding up the percentages of trips that had already departed to work and placing that sum into the percentage-returning column in the hour the evacuation order is called. For the other two trip types, it is assumed that a trip take less than one hour. After the evacuation order is called no more trips of the HBW, HBNW, and NHB type are made. This is shown in Table 8. The columns labeled

"% Departing" represent the number of trips that are departing in a period, while the columns labeled "% Returning" represent the number of trips that are returning in a period.

Table 8 Normal and Hurricane Hourly Trip Distribution (Evac. Order at Hour 10)

	Normal HBW		**Hurricane HBW**	
Hour	% Departing	% Returning	% Departing	% Returning
0	0.4	0.0	0.40	0.00
1	0.2	0.0	0.20	0.00
2	0.0	0.0	0.00	0.00
3	0.2	0.0	0.20	0.00
4	0.4	0.0	0.40	0.00
5	2.7	0.0	2.70	0.00
6	7.9	0.0	7.90	0.00
7	19.2	0.0	19.20	0.00
8	9.2	0.0	9.20	0.00
9	3.0	0.0	3.00	0.00
10	0.7	0.0	0.00	43.20
11	0.6	0.0	No Trips Made	
12	0.7	1.4		
13	0.6	1.4		
14	0.6	3.2		
15	0.6	5.7		
16	0.6	13.1		
17	0.6	11.8		
18	0.6	3.1		
19	0.6	1.7		
20	0.6	1.0		
21	0.0	2.9		
22	0.0	2.8		
23	0.0	1.9		

Using the hurricane evacuation rates shown in Figure 2, six new columns are added to the time of day table. These columns are the slow, medium, and fast evacuation percentages, shown in Table 9. The percent-returning column is populated with zeros to represent people not returning to their homes during the evacuation period. Cells that are empty implicitly have a value of zero because no one is departing or returning from these trip types at these times. Comparing Table 8 and Table 9, there are three hours of overlap with evacuation trips that are embarked on prior to the evacuation order. The three evacuation rates are modeled separately from each other and should not be combined. These values can be shifted up and down on the hour scale depending on what time the evacuation order is given.

Table 9 Evacuation Rates in Tabular Form (Evac. Order at Hour 10)

	Slow		Medium		Fast	
Hour	% Departing	% Returning	% Departing	% Returning	% Departing	% Returning
0						
1						
2						
3			← No Trips Made →			
4						
5						
6						
7	6.0	0.0	5.0	0.0	4.0	0.0
8	1.0	0.0	1.0	0.0	1.0	0.0
9	1.0	0.0	1.0	0.0	1.0	0.0
10	2.0	0.0	3.0	0.0	4.0	0.0
11	2.0	0.0	5.0	0.0	10.0	0.0
12	3.0	0.0	7.0	0.0	20.0	0.0
13	3.0	0.0	8.0	0.0	20.0	0.0
14	3.0	0.0	15.0	0.0	20.0	0.0
15	9.0	0.0	20.0	0.0	15.0	0.0
16	9.0	0.0	15.0	0.0	5.0	0.0
17	11.0	0.0	10.0	0.0		
18	13.0	0.0	5.0	0.0		
19	17.0	0.0	5.0	0.0		
20	10.0	0.0				
21	5.0	0.0				
22	5.0	0.0				
23						

These values may not be sufficient for a multi-day evacuation. If a multiday evacuation is expected then each day needs to be modeled separately. The Mississippi report gives some guidance on this matter recommending seventy-five percent of the evacuees leave on the first day, while the balance leave on the second day (MS HES 2001).

The PA→OD tool yields twenty-four matrices for each trip type (twenty-four hourly matrices per trip type times four trip types gives a total of ninety-six matrices) that enumerated how many trips would originate and terminate in each TAZ for each hour. This procedure is carried out for each of the three evacuation speeds. The only differences between the three speeds are the values located in the hourly table used in the process of turning the production-attraction matrices into the origin-destination matrices. These ninety-six matrices are added together for each hour so that twenty-four matrices (the sum of the four types of trips for twenty-four hours) are obtained. In order to let the assignment process clear all of the trips in case there are vehicles still using the roadway at the end of the twenty-fourth hour, up to ten additional matrices are included.

7.4.3 Traffic Assignment

Using DTA, the routes that people would take to get to the evacuation TAZs are determined. The thirty-four matrices from the previous section are used as the inputs for the traffic assignment. The "Depart Periods" toolbox is set to the number of departure periods. This value depends on which evacuation rate is being examined. The values for the fast, medium, and slow cases respectively are seventeen, twenty, and twenty-three hours. The "Total Periods" toolbox is set to one time step larger than the required amount of time to clear the network. This becomes an iterative process, though a good method is to initially set the total periods high to see what the clearance time is, and adjust it to correspond to this time. The BPR function is used with α ranging from 0.15 to 0.70. The storage capacity of each link is calculated by multiplying the number of lanes and length of the link by two-hundred and ten.

7.5 General Results

In this section, the results that are common to all three release speeds are examined. This section contains information such as the change in the number of trips made on a normal day as compared to an evacuation, some of the catchment areas for certain exit points, and the travel time from the larger communities to the exit points.

During the trip generation step, the number of productions by each TAZ in the event of an evacuation are calculated. The productions per household are generally one, as most households fit in one vehicle, but some TAZs produced multiple trips on average. When the evacuation productions for each zone are added together, 56,192 trips are made. Table 10, below, shows the number of trips of each type that are produced on both a normal day and an evacuation day. The decline in the HBW, HBNW, and NHB trip types are derived from the trips that are not made after the evacuation order. By examining Table 8 an example of the change may be found. 86% of the usual HBW trips are made on the evacuation day; this is obtained by summing the departing and returning percentages for the evacuation day. This directly corresponds to the HBW row in Table 10. The reduction in HBW trips is 13.6%. This can be done for each of the trip types. The numbers of trips that are generated by the hurricane are not excessive when compared against a normal day. This leads to the idea that the problem with the hurricane are not volume based, because the network can currently handle almost ten times as many trips as the hurricane produces, but rather are temporally based. In other words, problems occur due to the small number of trips being produced all leaving at nearly the same time.

According to these values, during the hurricane evacuation about half as many trips are made. Most of the HBNW trips are normally made after 10 AM. Since the hurricane forced people to forego making these trips, the total number of trips made significantly decreased. The total number of trips made during the day is highly affected by the number of HBNW trips that are not made. Most of the HBW trips are still made, though the return portion of the trips is dramatically accelerated. In other words, almost half of the trips had already been made before the evacuation is ordered; in order to bring those trips back to their home, that same percentage of trips had to be made going back home. If the evacuation is ordered earlier, around 5-6 AM, then there would be almost no trips made on the network, and almost all of the trips made for the day would be solely induced by the evacuation order.

Table 10 Trips Made With and Without a Hurricane

Trip Type	Normal	Evacuation	% Change
Hurricane	0	56,192	N/A
HBW	96,366	83,260	-13.6%
HBNW	179,255	28,322	-84.2%
NHB	75,903	12,904	-83.0%
Total	**351,525**	**180,678**	**-48.6%**

In order to determine where the hurricane evacuees are coming from and going to the evacuation trip production-attraction matrix can be examined. One example is shown below in Figure 15. These maps are created by copying and pasting the values from the production-attraction matrices into the TAZ dataview layer. This is then easily plotted using the built-in GIS tools of TransCAD.

Figure 15 shows the first and second highest utilized TAZs: TAZ 1035 to the north and TAZ 1002 to the west. The “other” category contains TAZs that fell under one trip originating in that TAZ. Because of the nature of the model used, it is likely some trips are made from each TAZ though many of these are negligible. This model does show that the TAZs that are closer to the region are making considerably more trips than the farther away TAZs. The road that the evacuees use in these segments are US 20 to the west and US 7 to the north.

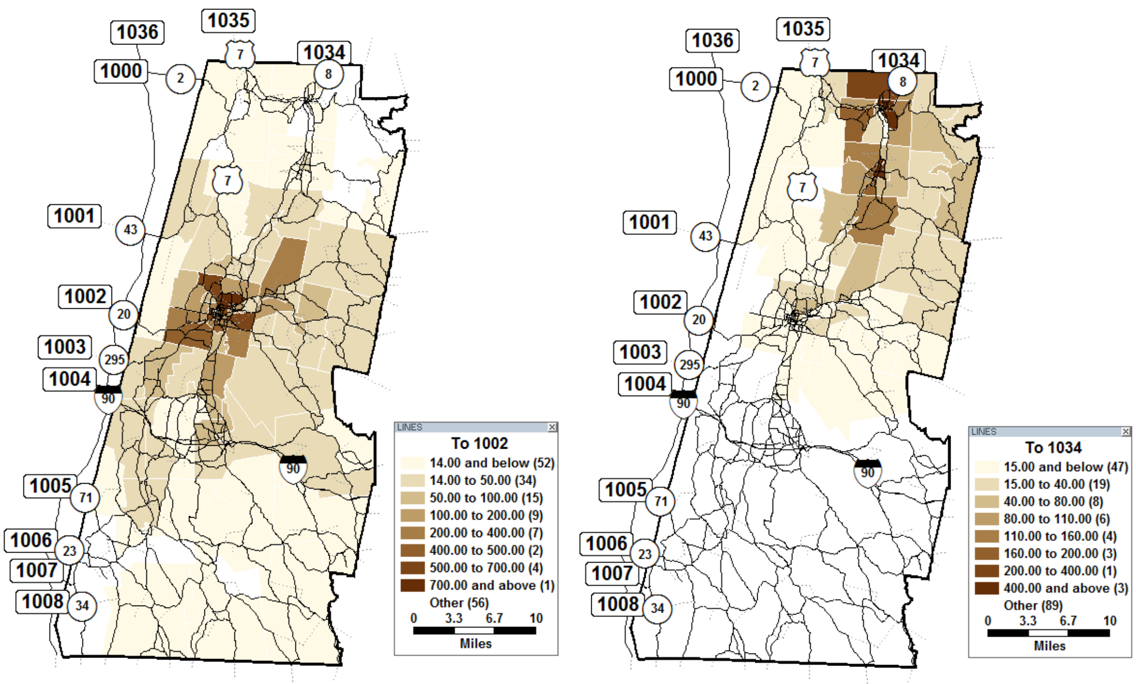

Figure 15 Trips made from the origin TAZs to the Evacuation TAZ 1002 and 1034.

There are a small number of zones that may experience problems concerning having enough vehicles to evacuate. The average number of vehicles per household is less than one for several of the TAZs. This implies that while some of the households may have more than one car, many houses have no cars. Either these residents must find a way to rideshare with nearby residents or they will need some form of public transportation (that is, buses) to assist them during the evacuation. These TAZs are shown in Figure 16. However, in these TAZs there is enough space in all of the vehicles (assuming four seats per vehicle) to evacuate. In TAZ 5, there is a high concentration of students and a low number of vehicles. There are not enough seats to evacuate everyone in this TAZ. This TAZ is shown in Figure 17. In this case, either the residents in the TAZ need to seek shelter within the TAZ or buses need to be focused to this TAZ. Ignoring other factors, TAZs that do not have enough vehicles to evacuate their entire populations should be given more attention than those that must rideshare to evacuate fully.

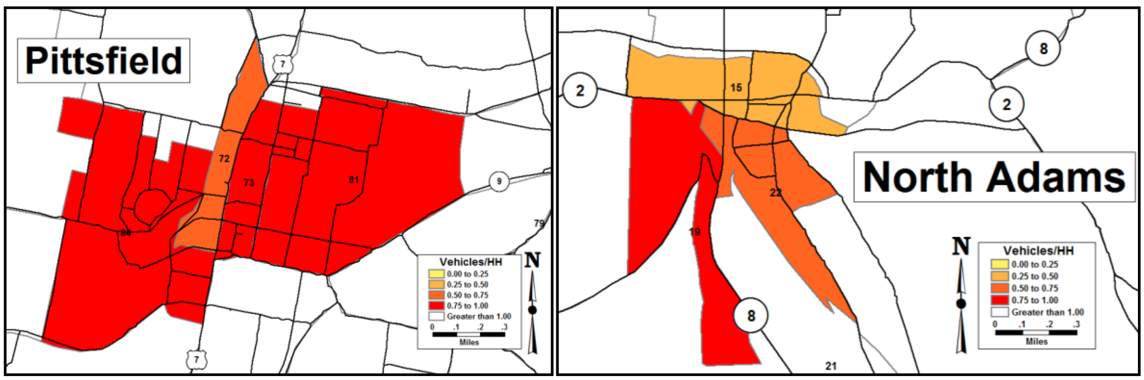

Figure 16 TAZs with a low vehicle per household density.

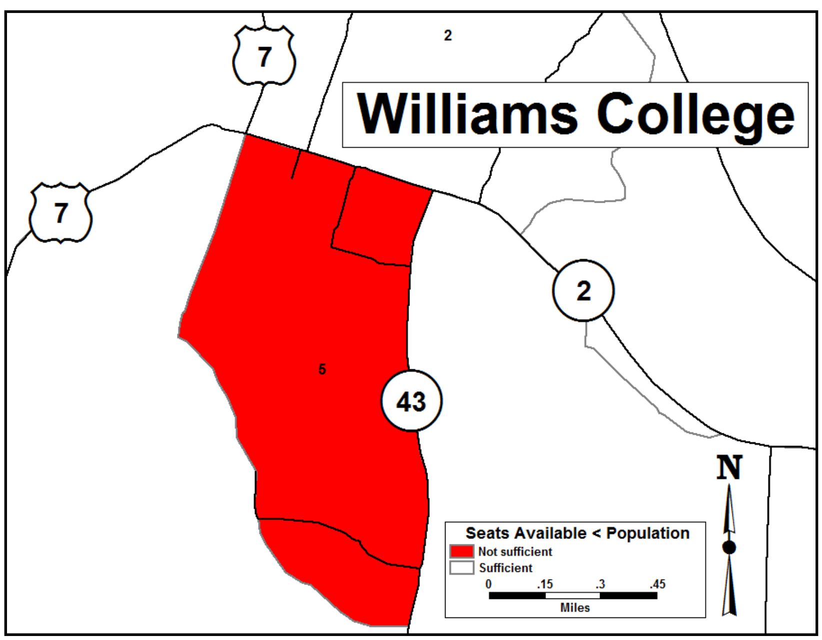

Figure 17 TAZ with insufficient seating available for the population

7.6 Release Rate Based Results

In the previous section, the results that applied to all of the release rates were examined. Those results are obtained before the release rates are used in the analysis and are therefore independent of the rate. They are results from step two (Trip Distribution) from the four steps of the planning model. There are several important issues to look at when examining a hurricane evacuation. One of the more significant measures of effectiveness of a hurricane evacuation is the clearance time. Clearance time is the length of time from when the evacuation is ordered until everyone (or a significant portion of the population) has left the county borders. Other measures are of value to different groups, such as volume to capacity (V/C) ratios, which are valuable to engineers, or congested speeds, which are valuable to the planners and the public. Another metric that is of some value is the flow, or volume, of vehicles passing in a given time. Volume on its own is not a significant indicator of the road condition, but locations with high volumes can quickly become disabled if there is an incident on the link.

The clearance times are obtained by searching the output of the DTA report for the first hour with no volume on any links. The clearance time is determined to be the length of time from when the evacuation order is called until the end of the last hour with nontrivial traffic. The results of the three evacuation speeds are found in Table 11. These times show that according to this model the faster, or sharper, that people evacuate the shorter the evacuation takes.

It is evident from these results that the time that it takes to fully depart is largely a function of the speed of the evacuation. It took about three hours after the last vehicle began its voyage for that vehicle to depart the county. All three of the rates would satisfy the requirement of evacuating all of the people before the hurricane force winds enter the county.

Table 11 Clearance Time of Each Evacuation Speed

Evacuation Speed	Clear By	Clearance Time
Slow	2 AM (next day)	16 hours
Medium	11 PM	13 hours
Fast	8 PM	10 hours

Table 12 provides the top three critical locations for each evacuation rate. These locations may exhibit a V/C ratio greater than or equal to one.

Table 12 Top Three Critical Locations for Each Evac. Speed and Critical Hour

Slow	Max V/C	Street		Street		Street
1	2.17	Simonds Rd. (US 7)	from	Main St.	to	State Line
2	1.66	West Housatonic (US 20)	from	Gale Ave.	to	Cen. Berkshire Blvd.
3	1.65	Richmond Rd.	from	Summit Rd.	to	Canaan Rd.
Med.	**Max V/C**	**Street**		**Street**		**Street**
1	2.52	Simonds Rd. (US 7)	from	Main St.	to	State Line
2	1.73	State Line Road	from	Main St.	to	Albany Rd.
3	1.70	Richmond Rd.	from	Summit Rd.	to	Canaan Rd.
Fast	**Max V/C**	**Street**		**Street**		**Street**
1	2.78	Simonds Rd. (US 7)	from	Main St.	to	State Line
2	1.87	State Line Road	from	Main St.	to	Albany Rd.
3	1.64	Massachusetts Ave.	from	Marshall St.	to	Simonds Rd.

The travel times are what the general public finds most important— they want to know how long it takes them to get out of harm’s way. The DTA reports the congested equilibrium travel time on each link. By using these values as the travel time to calculate the shortest-path between any two centroids, the travel time between communities and evacuation TAZs can be found. Four of the larger communities’ travel times are reported in Table 13 and Table 14.

Table 13 shows the time that it takes to travel from a community to the exit of the county at the farthest away exit, denoted by the route number, during the period with the highest volume of vehicles using the roads. Generally, the values stay close to the free flow travel time.

Table 14 shows the travel times during the same hours as above, but these values are heading from the listed community to that TAZ (indicated by the road/route number) that is most used by that community. A full listing of the travel times is shown in Table 15. Bolded boxes denote the most used evacuation TAZs for the corresponding community.

Table 13 Longest Congested Travel Times (except US 7)

From	**To**	**Evacuation Rates (units in minutes) [hour examined]**			
		Free Flow	Slow [7-8 PM]	Medium [3-4 PM]	Fast [2-3 PM]
North Adams	Rt. 34	92.9	93.1	94.2	94.4
Pittsfield	Rt. 34	66.0	66.5	67.4	67.7
Stockbridge	Rt. 2	65.4	66.6	68.8	69.9
Lenox	Rt. 2	55.0	56.4	58.8	60.3
Great Barrington	Rt. 2	70.7	71.6	73.9	74.7

Table 14 Congested Travel Time to Most Used Evacuation Zone

From	**To**	**Evacuation Rates (units in minutes) [hour examined]**			
		Free Flow	Slow [7-8 PM]	Medium [3-4 PM]	Fast [2-3 PM]
North Adams	US 7	26.2	64.6	137.6	178.3
Pittsfield	US 20	31.8	49.2	47.0	51.2
	Rt. 295	34.5	43.5	51.3	52.4
Stockbridge	Rt. 23	34.8	36.5	38.4	39.3
Lenox	Rt. 295	29.1	31.3	37.8	39.0
	Rt. 102	27.8	28.8	34.7	36.2
Great Barrington	Rt. 23	28.3	30.1	31.8	32.8

The most extreme rate in all of the cases is at Simonds Road where the highest rates of congestion are predicted. For the slow rate, these travel times are 1.0 to 2.5 hours.

The medium rate has values ranging from 1.0 to 3.0 hours. The fast rate's travel times are approximately 3.0-4.0 hours. This is due to the high volumes that are using the road causing significant delays.

7.7 Lessons Learned

Some lessons were learned during the modeling process:

- Other programs other than TransCAD can help make the modeling process more efficient. Many of the trip generation steps are very easy to complete inside of a spreadsheet environment rather than the database environment of TransCAD.
- Using the Warm Start option inside the DTA module can help the program achieve convergence much faster. Once results from a single run have been obtained, select results can be added to the network and then warm started into the next run. This is helpful when running the fast evacuation speed. This operation by itself takes a considerable amount of time, but the warm start feature decreases this time. In this case, the modeling time is not extreme. If a finer time resolution were used, then this tool would be useful.
- The "depart periods" and "total periods" toolbars must be completed. The other option would be to add empty matrices to the origin-destination matrices. TransCAD does not treat a matrix full of zeros the same as a matrix after the last depart period. TransCAD uses one measure of convergence for all of the study periods, and if too many zero matrices are added they will overshadow the congested periods.
- One-hour increments give an adequate general picture of where people will go and what routes they will use. A smaller time increment is necessary for a more detailed picture of what is happening.

Table 15 Travel Time from Communities to Exit Points

		Town TAZ	16	74	99	108	139
TAZ ID	**Road**	**Speed**	**North Adams**	**Pittsfield**	**Lenox**	**Stockbridge**	**Great Barrington**
1034	**Rt. 8**	FF	20.5	46.2	53.6	65.6	70.8
		Slow	20.7	46.7	54.0	66.0	71.1
		Med	20.9	47.5	54.8	66.7	71.8
		Fast	21.1	47.7	54.9	66.8	71.9
1035	**Rt. 7**	FF	26.2	43.0	51.1	61.5	66.7
		Slow	64.6	73.5	79.9	86.6	88.7
		Med	137.6	149.8	151.4	153.0	153.5
		Fast	178.3	205.4	205.4	205.4	205.4
1000	**Rt. 2**	FF	37.6	46.9	55.0	65.4	70.7
		Slow	38.2	48.6	56.4	66.6	71.6
		Med	40.5	50.9	58.8	68.8	73.9
		Fast	42.5	52.9	60.3	69.9	74.7
1001	**Rt. 43**	FF	44.0	37.2	40.3	45.7	51.0
		Slow	45.2	40.0	47.7	46.4	51.7
		Med	48.4	44.1	51.7	48.8	54.0
		Fast	50.7	47.5	54.5	50.7	55.7
1002	**Rt. 20**	FF	55.1	31.8	29.8	32.9	38.2
		Slow	56.4	49.2	40.8	33.6	38.8
		Med	59.6	47.0	41.3	35.8	41.0
		Fast	61.9	51.2	45.8	37.6	42.6
1003	**Rt. 295**	FF	62.4	34.5	29.1	25.2	30.5
		Slow	64.1	43.5	33.1	25.9	31.1
		Medium	67.3	51.3	37.8	28.1	33.3
		Fast	69.6	52.4	39.0	29.9	34.9
1004	**I-90 Rt. 102**	FF	67.8	39.9	27.8	22.1	27.4
		Slow	69.5	44.2	30.6	22.7	28.0
		Med	72.7	48.7	34.7	24.8	30.0
		Fast	74.4	49.8	36.2	26.3	31.4
1005	**Rt. 71**	FF	81.0	54.1	39.9	34.1	25.9
		Slow	82.2	56.3	42.7	34.1	25.9
		Med	85.0	58.3	44.0	34.4	26.2
		Fast	85.2	58.7	44.2	34.6	26.5
1006	**Rt. 23**	FF	84.9	58.0	43.9	34.8	28.3
		Slow	85.5	59.1	45.3	36.5	30.1
		Med	87.7	61.5	47.3	38.4	31.8
		Fast	87.8	62.0	48.0	39.3	32.8
1007		FF	89.3	62.4	48.2	39.2	32.6
		Slow	89.5	62.9	49.0	40.0	33.5
		Med	90.6	63.8	49.5	40.5	34.0
		Fast	90.8	64.1	49.6	40.7	34.2
1008	**Rt. 34**	FF	92.9	66.0	51.8	42.8	36.2
		Slow	93.1	66.5	52.6	43.6	37.2
		Med	94.2	67.4	53.1	44.1	37.6
		Fast	94.4	67.7	53.3	44.3	37.8

CHAPTER 8

CASE STUDY IV: MULTIREGIONAL HURRICANE

The final modeling activity is a hurricane evacuation on a much larger network. The same methodology laid out in Chapter 7 regarding the single county hurricane evacuation is followed to obtain the results for this chapter. The trip distribution step is altered: only the slow and fast departure rates are used. This allows the "best case" and "worst case" mandatory evacuation scenarios to be examined. When assigning the traffic on the network the slow release rates results are warm started into the fast release rate's run. This populates the network with a starting point to begin the algorithm, and it decreases the amount of time needed to obtain dynamic convergence.

8.1 Data Cleaning

The data obtained from the three regions is not uniform. The amount and scope of the data varied between the three regions. Each region had some similarities and differences that were accounted for before the modeling activities began. The main differences between the data are shown below in Table 16.

Table 16 Differences Between the Three Data Sources

	PVPC	FRCOG	BRPC
Year	2000	2003	2000
Demographic	Disaggregate	Aggregated	Aggregated
Level of Road Detail	High	High	Low
Network Capacity – Hourly	Uniform	Uniform	Uniform
Network Capacity – Daily	Different	Uniform	Uniform
Friction-factor Method	Table	Table	Exponential

The models are incorporated together first using the assumption that the population of Franklin County has not grown significantly from the base year of the data until 2003. This is consistent with data provided by Franklin County estimating a growth of 4.7%. The PVPC data is disaggregated into household size and number of autos owned (one person-zero cars, two persons-four cars, up to four persons-four cars). These are collapsed into number of households, number of vehicles, and population. For example, the total of all of the households with three vehicles owned for a specific TAZ is 106; this value multiplied by three gives a total of 318 vehicles. This is completed for each of the categories and then summed across to obtain the total number of vehicles. The same can be done for the population. The number of households with two people per household is 357; this multiplied by two is 714 people. These are added up across each number of household. The total number of households is obtained by summing the number in each category without multiplying any variables. This process is shown in Table 17. The grand totals for the specific example are 2,301 vehicles, a population of 2,750, and 1,075 households in the TAZ. Employment data is not aggregated in any way and is left untouched.

Table 17 Example of Data Aggregation for a Single TAZ

		Autos Owned					
	TAZ X	0	1	2	3	4	Pop. Subtotal
# Per HH	1	28	170	15	2	2	217
	2	10	135	183	19	10	(357*2)=714
	3	5	42	79	41	18	555
	4	7	44	118	44	103	1,264
	Veh. Subtotal	0	391	790	(106*3)=318	532	

The networks are combined in TransCAD using the GIS map editing tools provided. The roads at the network boundaries are connected, external TAZs that have now become internal TAZs are deleted, and the given normal-day production-attraction data is rebalanced to account for the removal of several of the external TAZs. Wherever two data sets met, the network is checked to make sure that the links are connected and that the network capacities are the same or very similar. In a small number of cases the daily capacity data is different; this problem occurred when comparing some PVPC points with the other two regions. In most cases, however, the hourly capacities are the same. A very small number of the hour capacities are different. When they are different, the difference ranged from a few dozen to a few hundred vehicles per hour. In these cases, the difference is neglected and all of the link capacities are kept at their original value. The exponential model is used to distribute the normal day trips that occur before the evacuation. Several of the links were checked across the models to determine if the exponential model would give the same order of magnitude in both the stitched regional models and the single county models. The values are similar enough to not warrant the re-calibration of a multi-region model. This step only models what would happen before the hurricane evacuation begins, which is not the concern of this document. After the hurricane evacuation order is given, the trips are all changed to the same model. If the model were to be used for regional modeling activities then the model should be recalibrated.

8.2 Modeling Process / Results

The multiregional hurricane affects all three of the regional planning agencies. This can be seen as an extension of the BRPC/Berkshire County hurricane modeling activities. The three regional demographics have already been outlined in the previous chapters and readers that are interested in that information are directed to those chapters.

The scenario is similar to the BRPC model. A hurricane is heading up the Connecticut River towards Vermont and then toward Montreal, Canada. This path roughly follows the path of the New England Hurricane of 1938. This hurricane was a category 3 storm that devastated the region when it rolled through in the summer of 1938.

8.2.1 Trip Generation

The trip generation process is completed using the procedure laid out in the previous hurricane chapter. The total productions are lower than the BRPC-only case as can be seen in Table 18. The values are still low on a trips taken per household basis, and they are at the lower end of the percent of vehicles used.

Using the path of the New England Hurricane of 1938 as a guide for the trajectory of the proposed hurricane path, evacuation points are chosen. The path splits the region in half, causing people to want to head east towards Boston or Worcester, MA or west towards Albany, NY or other upstate New York areas. The same points that are used in the BRPC model are used in the multiregional model. The eastern exit points along the borders of the remaining three counties are used as evacuation points in the multiregional model. These evacuation points are shown in Figure 18.

Table 18 Productions by Veh. Trips per HH (Left) and Percent of Vehicles (Right)

Area	Rate	Area	Rate
Alabama	1.16-1.36	Apalachee Bay (FL)	65-75%
Apalachee Bay (FL)	1.20-1.30	NW Florida (FL)	65-75%
NW Florida (FL)	1.16-1.36	Tampa Bay (FL)	65-75%
Mississippi	1.15-1.49	Georgia	65-75%
		New York	70%
		North Carolina	60-70%
		South Carolina	65-75%
Berkshire County	1.01	Berkshire County	66%
Three Region	**1.00**	**Three Region**	**64%**

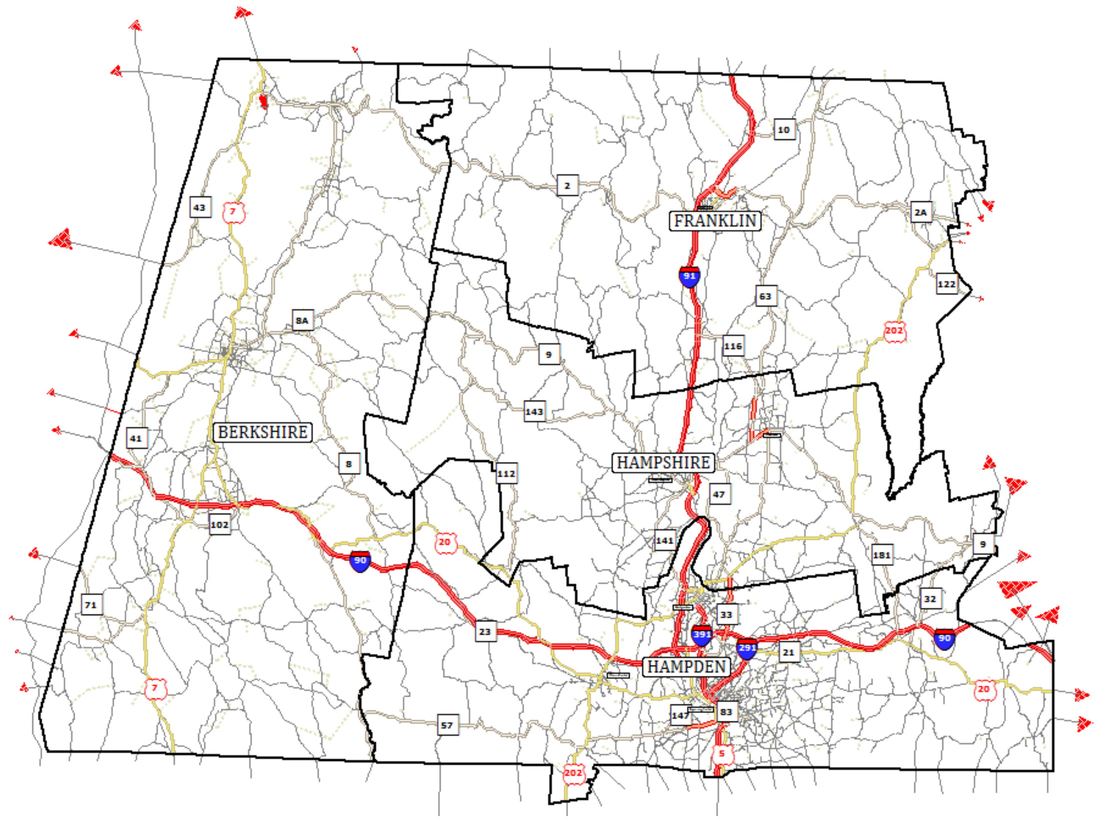

Figure 18 Three-region area with evacuation points denoted with filled in triangles.

Major exits used in this model are Interstate 90 (25%), Rt. 2/2a (16%), US 7 (7%), and US 20 (5%). The eastern portion of the region has a much higher population than the western portion. Springfield is located around the intersection of Interstate 90 and Interstate 91. This population uses Interstate 90 extensively for the evacuation. The residents of Greenfield to the north in Franklin County use Rt. 2, and the residents of Pittsfield use US 20 and 7.

8.2.2 Trip Distribution

Again, the gravity model is used to model the hurricane. Each trip type: HBW, HBNW, and NHB, had an exponential friction-factor coefficient of 0.16, 0.14, and 0.13, respectively. For the evacuation trip type, the default value of 0.125 is used.

After the distribution process, the numbers of people leaving from each TAZ to each evacuation exit was obtained. The counties that are heading primarily west and east are shown in Figure 19. The counties that are exclusively heading either west or east are shown in blue or yellow respectively, while counties that are heading both east and west are shown with varying shades and intensities of a mixture of blue and yellow (presumably green). As should be expected, these counties are primarily found in the middle of the four-county area. Counties that are making more trips, indicative of the TAZ's population, are colored darker.

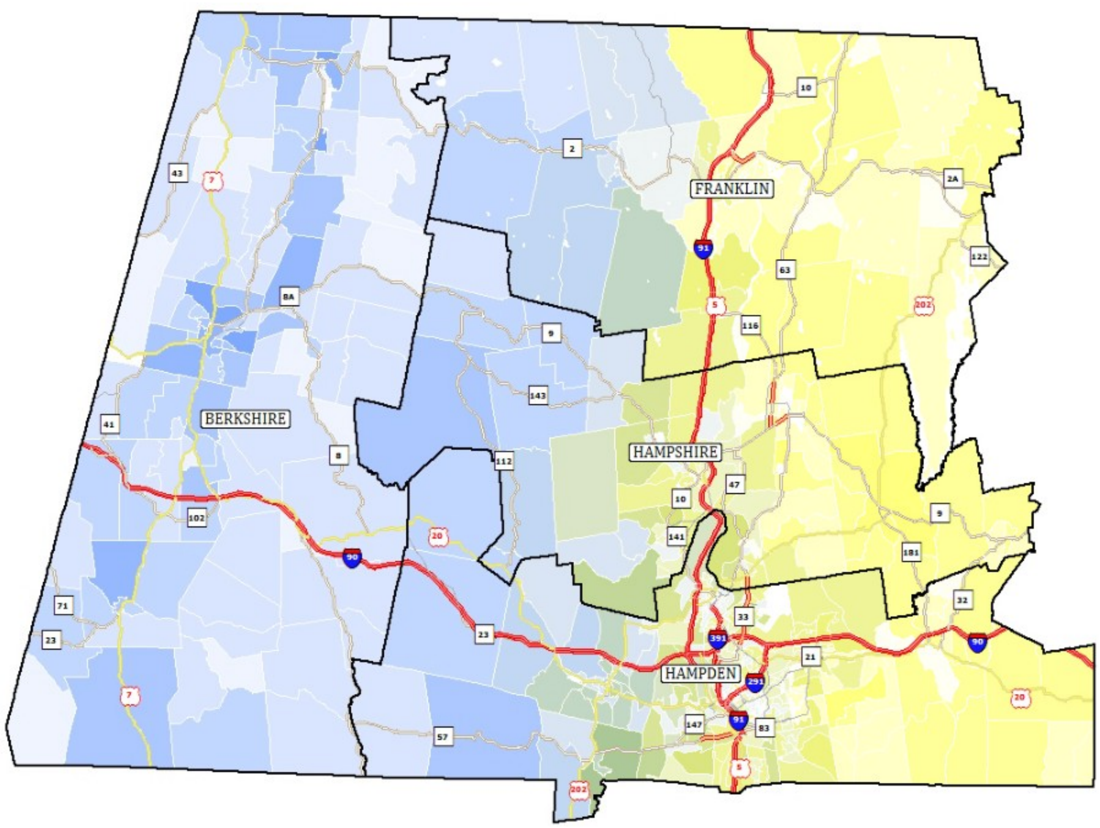

Figure 19 Counties heading west (blue), east (yellow), and mixed (green).

Following this, the origin-destination matrices are obtained for each of the twenty-four hours of the day of the storm. This is completed by editing the time-of-day table. The procedure that is followed for this portion of the modeling is noted in the Trip Distribution portion of the BRPC hurricane model. After the twenty-four hours of the storm day are obtained, up to ten matrices are added on top of these to simulate the hours after midnight that are available for modeling.

8.2.3 Traffic Assignment

Using the matrices obtained in the previous section, the "Depart Periods" toolbox is filled in with values based on which evacuation rate is being examined. The "Total Periods" toolbox is filled with one time step more than is required to clear the network. Because of the substantial number of links on the network, the DTA takes a significant amount of computing time. To reduce this time, the first modeled period is 5-6 AM. This reduces the computing time by removing several modeled periods. This is the first period, and the "Depart Periods" and "Total Periods" are counted starting from this time. The duration of a period is one hour. The storage capacity of the links is added to allow the DTA to permit people to divert their routes based on the queue.

8.3 General Results

As the majority of the process is the same for the isolated county as well as the full four-county area, the same sorts of results are obtained.

Similar to the Berkshire County model, the overall number of trips decreased from before the hurricane to after the hurricane. These results are shown below in Table 19. The largest decrease in trips is a result from most of the HBNW trips not being made. The total number of trips has actually decreased by half.

Table 19 Trips Made With and Without a Hurricane

Trip Type	Trips Before	Trips After
Hurricane	--	318,056
HBW	525,791	454,283
HBNW	1,064,603	168,207
NHB	425,378	72,314
Total	2,015,772	1,012,861
% of Original	50%	

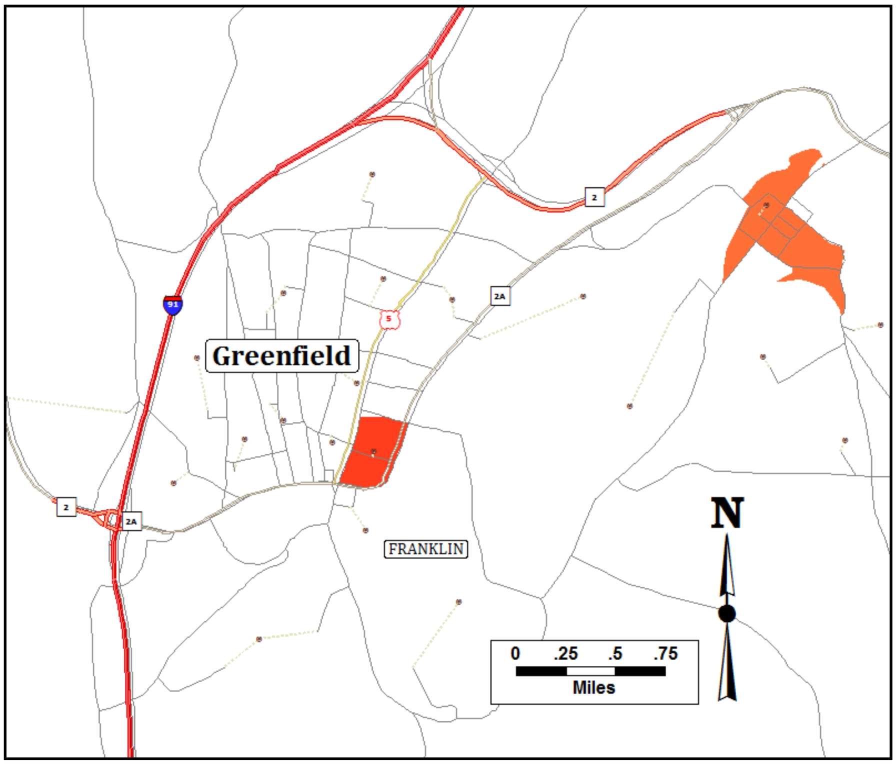

Figure 20 Franklin County TAZs with less than one vehicle per household.

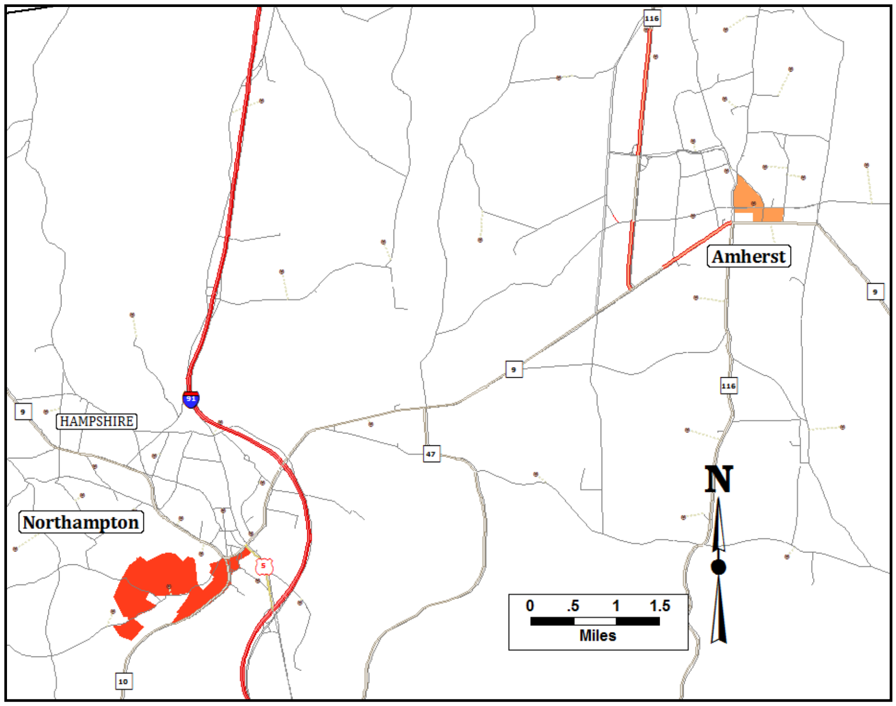

Figure 21 Hampshire County TAZs with less than one vehicle per household.

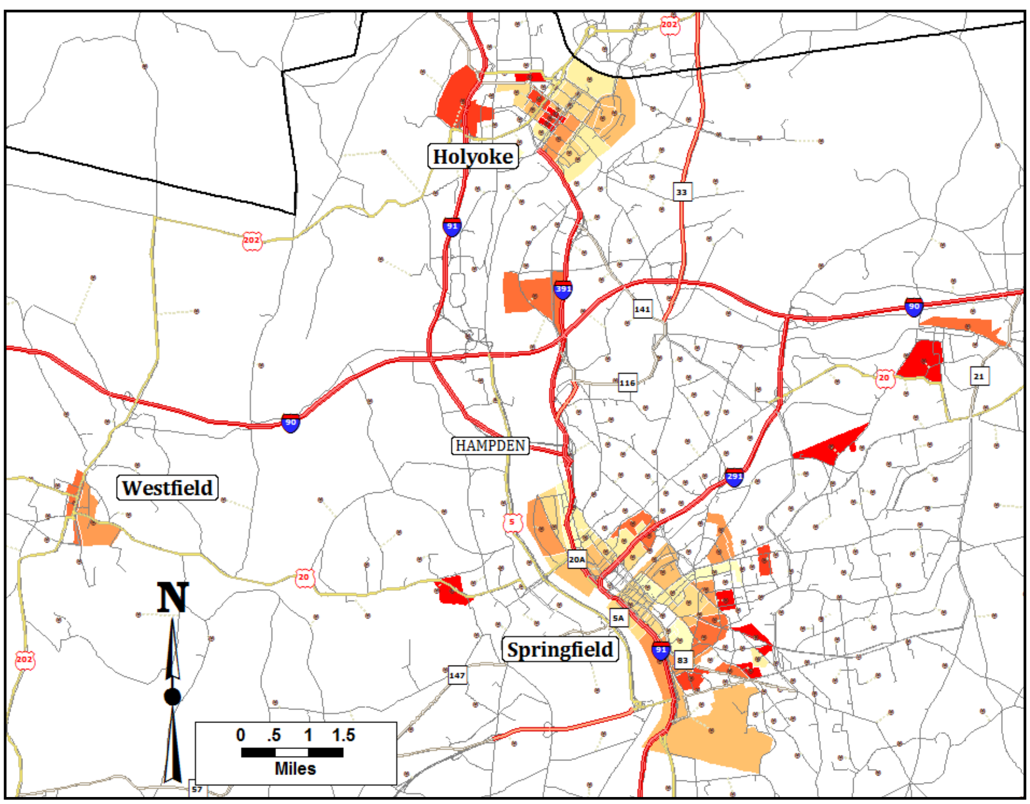

Figure 22 Hampden County TAZs with less than one vehicle per household.

The TAZs that have less than one vehicle per household are shown in Figure 20, Figure 21, and Figure 22. The results for Berkshire County have already been shown in an earlier section. There are no additional TAZs (beyond the TAZ in Berkshire County) that do not have sufficient vehicle space taking into account the assumed capacity of the vehicles. The only TAZ in the region is shown in a previous section.

8.4 Release Rate Based Results

One of the most important results for the hurricane evacuation is the clearance time. These are shown below in Table 20. A comparison of only the Berkshire County results is shown in Table 21.

Table 20 Evacuation Speed for Four Counties

Evacuation Speed	Clear By	Clearance Time
Slow	1 AM	16 Hours
Fast	8 PM	10 hours

Table 21 Comparison with Berkshire County Results

Evacuation Speed	Clearance Time Only Berkshire	Clearance Time in Four County
Slow	16 hours	16 hours
Fast	10 hours	10 hours

A very small trickle of vehicles remains on the network from 8 PM until the actual clearance time at 5 AM. If 8 PM is taken as the time when the vast majority of the vehicles are out of the county, then the clearance times line up very well. The amount of vehicles that are added to Berkshire County is not significant enough to explain a ten-hour extension of the clearance time in the county. The extra vehicles may be a result of the dynamic traffic assignment algorithm.

There are only about 850 modeled miles of roadway in Berkshire County. There is about 3,200 miles of modeled roadway in the four-county model. It should be expected that considerably more links would be critical links in the four-county model. Figure 23 presents the congested links during the fast evacuation rate from 2 to 3 PM, the hour with the most traffic on the network. Grey links have a V/C ratio less than one, while the V/C ratios increase from yellow to orange to red and finally to pink with the highest V/C ratios. There is minor congestion of people using US 7 in the northwest corner of the state to evacuate. This is also seen in the Berkshire County model presented earlier. There is significant congestion in the northeast corner from the people using Rt. 2 and 2a to exit the county. The most congestion is seen in the southeast corner. These people are using Interstate 90 to evacuate to the east towards Worcester and Boston. Some people from Springfield do use Interstate 90 to evacuate to the west. As is expected, the congestion is focused near the locations with the highest percentage of people using the routes to evacuate. There is a section in-between the people evacuating to the east and the people evacuation to the west that is not very congested. In addition, most of the east-west roads in the middle of the four-county region are moving smoothly.

The equilibrium travel times during the time with the most congestion is shown below in Table 22. These values represent the travel time an individual would face if they left their TAZ at the beginning of the hour and headed to the listed exit. The travel time increases as the congestion increases. The travel time almost doubles under the slow case and more than triples in the fast case.

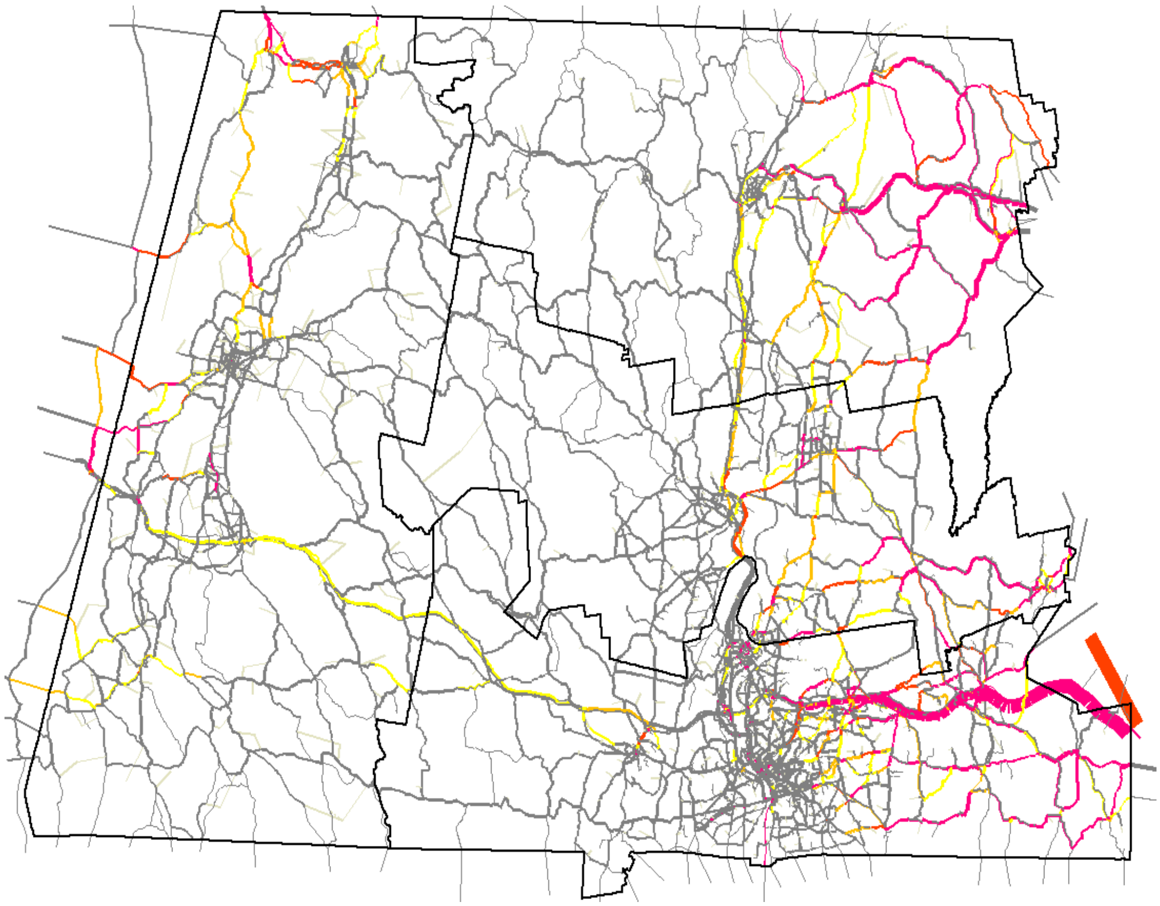

Figure 23 Flow and V/C ratio on the network during the hour of 2-3 PM.
Grey (Low V/C) → Yellow → Orange → Red → Pink (High V/C)

Table 22 Congested Travel Time to Most Used Evac. Zone (Four-County Case)

		Evacuation Rate (units in minutes) [hour examined]		
From	**To**	**Free Flow**	**Slow [8-9]**	**Fast [2-3]**
Pittsfield	US 20	31.8	53.9	97.2
Springfield	Interstate 90	44.5	200.9	270.4
Amherst	Rt. 2	46.9	141.6	211.1
Greenfield	Rt. 2A	41.2	184.8	256.6

The results from Pittsfield to US 20 agree well with the results found for the Berkshire County only scenario. The travel time is nearly 54 minutes in this case and is 49 minutes in the Berkshire County-only case. The fast travel time is almost two times higher; in other words, the vehicles are moving half as fast as the results from the Berkshire County only scenario.

8.5 Lessons Learned

Several lessons were learned during the modeling process:

- Other programs other than TransCAD can help make the modeling process more efficient. Many of the trip generation steps are very easy to complete inside of a spreadsheet environment rather than the database environment of TransCAD.
- Using the Warm Start option inside the DTA module can help the program achieve convergence much faster. Once results from a single run have been obtained, select results can be added to the network and then warm started into the next run. This is helpful when running the fast evacuation speed. This operation by itself takes a considerable amount of time, but the warm start feature decreases this time.
- The "depart periods" and "total periods" toolbars must be completed. The other option would be to add empty matrices to the origin-destination matrices. TransCAD does not treat a matrix full of zeros the same as a matrix after the last depart period. TransCAD uses one measure of convergence for all of the study periods, and if too many zero matrices are added they will overshadow the congested periods.
- One hour increments give an adequate general picture of where people will go and what routes they will use. A smaller time increment is necessary for more detailed picture of what is happening.

CHAPTER 9

DISCUSSIONS AND CONCLUSIONS

This document began with a review of what has been done previously with a few different evacuation modeling packages. Following this, several different case studies are presented that used TransCAD and the four-step transportation modeling process to emulate what might happen in a few evacuation scenarios. Results that can be obtained for each of the case studies are presented inside the section of each individual scenario. In two of the case studies, two different trip generation models are posited, while one did not alter the productions and attractions from the regional planning model. Three of the case studies used dynamic traffic assignment and one used static traffic assignment. Many of the processes in the model are left unaltered. These are the mathematical algorithms to find the shortest-path matrices, production-attraction matrices, and the traffic assignment. The processes are unchanged, but the inputs are changed.

9.1 Positive Aspects of Using TransCAD

In many of these steps, TransCAD performed without a hitch. In other portions, some issues arose. This section discusses what TransCAD can do, what it cannot do, and things that are difficult to do that are not a fault of the program.

TransCAD is a very powerful and nimble program. It is able to handle the volumes of data that are thrown at it, and complete calculations in a very quick manner. Assuming that the inputs are correct, TransCAD can handle most of the steps well. The GIS tools that are included with the software easily allow the selection of links that need to be disabled based on the location of the links in certain areas. The dynamic traffic assignment module is user friendly and straightforward. This allowed the chemical spill scenario (in which a segment of roadway is closed for only one period) to be completed efficiently. TransCAD also provides an excellent suite of mapping, charting, and graphing utilities. For the dynamic traffic assignment, TransCAD automatically provides a toolbar that allows the user to scroll through time and visualize the state of the roadway. These tools are very useful for logically presenting the data to interested parties.

9.2 Negative Aspects of Using TransCAD and the Proposed Models

The areas that TransCAD can be cumbersome are getting the data from one step to the next. For example, the process of specifically balancing the productions and attractions proportionately based on a weighted percentage is difficult to complete in TransCAD. It becomes even more difficult if certain TAZs are supposed to be set to specific values. The process of calculating the productions is quite simple. The weighted percentage portion causes the issues. However, a redeeming feature of the program is how easy it is to move data between a spreadsheet program and TransCAD. There is the option to import/export or the data can simply be copied and pasted into or out of the TransCAD dataviews. As detailed in the methodology from the previous chapters, this issue only arises in the hurricane and flood case studies. The problem is compounded in the flood scenario because of a limitation of the dynamic traffic assignment algorithm. The dynamic assignment module in TransCAD currently allows incidents to be placed on roads during specified periods. It does not allow multiple links to have their capacities manipulated during multiple periods. The flood scenario had multiple roads becoming inundated as time passed. Had TransCAD been able to disable links over the course of an analysis period, a static assignment approach would not have been necessary. The periods are extended to allow trips to finish within the time step. It order to run the traffic assignment each of the trip types (generally HBW, HBNW, and NHB, but in these cases also an EVAC trip type) must be added together to obtain hourly origin-destination matrices. When completing the traffic assignment over a single period TransCAD provides the option to do a "Quicksum". This simply adds together all of the matrices. It does not allow the user to add across trip types for each hour. There are tools that allow the user to complete this manually, but the dynamic assignment tool requires total origin-destination matrices of a small granularity. The manual method would become extremely burdensome if a small granularity and a long analysis period are used. This can be overcome using the extremely powerful GISDK package that comes with TransCAD. TransCAD is written in GISDK and the associated language. This shows the power provided by the developer's kit. A macro or a program could be written that would easily handle adding together the origin-destination matrices. This option should be available without any additional programming.

There are also several problems that can arise that are not TransCAD's fault. Some tasks are easier to complete in a spreadsheet program rather than in TransCAD. TransCAD works as a database instead of a spreadsheet so this is expected. It is built to handle large amounts of data. These results in general could be avoided if a different approach is used to model the evacuation. The models presented here yield entirely reasonable results for the given case studies, but they are not the only methods that could be used to generate the productions and attractions. The other place that can be changed in the modeling process is in the trip distribution step. This document uses the doubly constrained gravity model with various methods of obtaining the friction factors. The friction factor for an evacuation type trip has not had a large amount of research completed on it, and the research that has been completed may not be applicable to the northern states where people most likely do not perceive the threat of a hurricane as much as the southern states.

An underlying assumption of the traffic assignment algorithm is that people have full and perfect knowledge of what is happening on the network. This may be accurate enough for commutes to work and to the store; people know their options well and can make an informed decision. During an evacuation, this may not hold true. The routes they are using may be unfamiliar. They probably do not know what routes will be heavily congested.

There are issues regarding the model that is used to recreate the hurricane evacuation productions and attractions. First, the operator must choose what TAZs the people use to evacuate. During the modeling process, preliminary results based on an assumed set of TAZs were shown to the county representatives and changes had to be made based on their input. The shape of the county limited the choices of TAZs that could be chosen, and the fact that the evacuation TAZs had to modified illustrates that even on a simple county it may not be so straightforward to choose the evacuation TAZs. Second, this model does not take into account any external to external (or through) trips. This could matter more depending on the layout of the roads in the examined county. Comparing the evacuation of Berkshire County and the four-county evacuation, a small number of trips would head through Berkshire County to evacuate. In this case, there is enough knowledge to determine how many trips enter the county, but many counties may not have other regions' models. This requires an estimation of how many trips may head through their county.

There are also some issues regarding the flood evacuation model. The amount of trips that the flood produces is small. It is difficult to determine what impact, if any, the evacuation trips are having on the network. This is complicated by some of the locations of the centroids and centroid connectors in the TAZ. Some of the centroid connectors connect to the links far away from the flooded area. The links that are near the flood may not be used at all in the model, but they certainly would be used during an actual evacuation. Link connectors may be needed to be added closer to the evacuation area to allow traffic to use those links. This is shown in Figure 24. In “A and B”, the blue line indicates the extent of the flood. In these parts, the flood has not yet disabled any links. In “A”, there is no opportunity for traffic to use the inundated portion of the network. “B” adds a link connector that would allow traffic to use these roads to evacuate. Some of the evacuation trips may still use the other connectors, but this way there is a route that is in the inundation area. Another problem exists if the centroid is inside of the inundated area, and there are no link connectors to the non-flooded network; this is shown in “C”. In “C” and “D”, the flood has already occurred and has disabled the links within the blue section. No vehicles can access this TAZ due to the disabled roads. Roads must be activated to allow traffic to use the TAZ, or a link connector that extends out to the non-flooded region must be added, this correction is shown in “D”.

The evacuation trips are drastically overshadowed by the problem of the riverside links being submerged. The overall shift in the traffic patterns outweigh any of the problems caused by the few thousand evacuation trips. The evacuation trips do not have to go very far to get out of the flooded region; generally, this distance is less than 1,000 feet. After this, the people are out of the path of the flood, and need to get to the shelters.

The time frame of people getting to shelters is not as dangerous as the time it takes people to move hundreds of feet away from their homes.

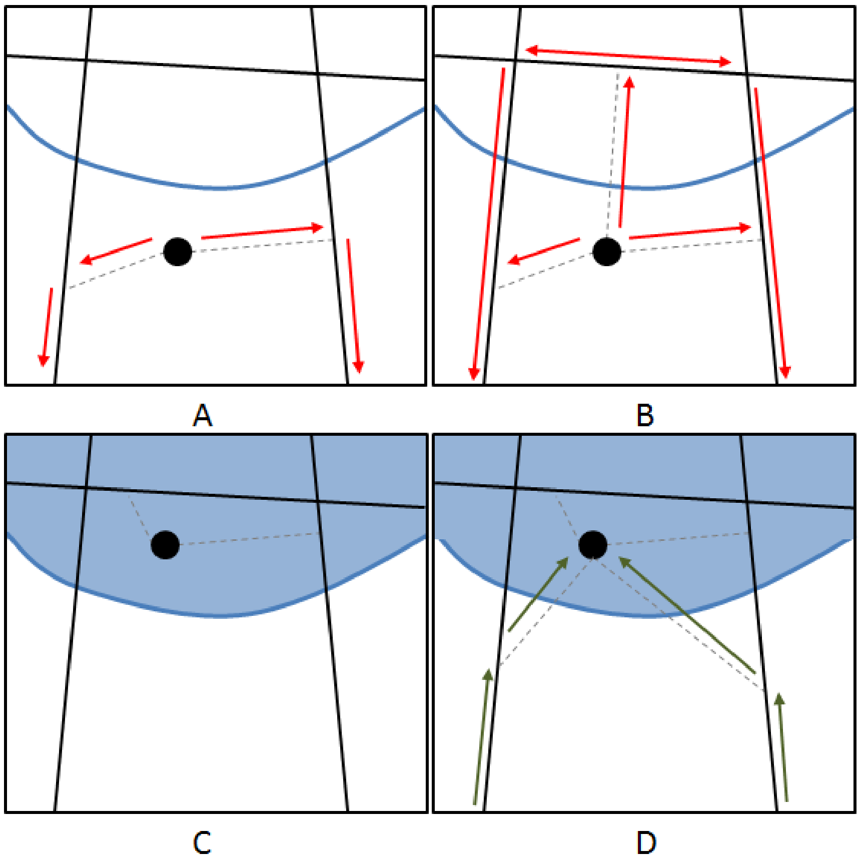

Figure 24 Problems with the locations of the centroids and connectors.

9.3 Recommendations

Some recommendations regarding TransCAD are:

- Add the capability to sum across like periods for multiple trips types without the programming of a macro in GISDK. This is a necessary step to run a dynamic traffic assignment.
- Allow multiple links' capacities to be affected differently during different periods. Extra columns could be added to the network that would list the percentage of the capacity to reduce and the period after the first period for the link to have its capacity

reduced. If the link capacity changes over several periods then perhaps another set of columns could be used.

Other recommendations can be based on the model used with TransCAD:

- Continue studying evacuation production and attraction methods that can be easily implemented into the four-step transportation planning model. The models presented here are adequate for the evaluation of TransCAD, but the models need to be tested more thoroughly to ensure the accurate generation of trips.
- Conduct more research on the parameters of the gravity model to determine what the trip length distribution would be in the event of a hurricane in the Northeastern United States.

BIBLIOGRAPHY

AL HES. "Alabama Hurricane Evacuation Study Technical Data Reort." 2001.

Andem, Santosh K. *A Comparative Analysis of Hurricane Evacuation Traffic Conditions Using Static and Dynamic Traffic Assignments.* Louisiana State University, 2006.

Blumenthal, Ralph. "Miles of Traffic as Texans Heed Order to Leave." *New York Times*, September 23, 2005: http://nytimes.com/2005/09/23/national/nationalspecial/23storm.html.

Bureau of Public Roads. *Traffic Assignment Manual.* Washington D.C.: U.S. Department of Commerce, Urban Planning Division, 1964.

Caliper Corporation. "TransCAD Manual." *Travel Demand Modeling with TransCAD.* no. Version 5.0. 2007.

Chakraborty, J., G. A. Tobin, and B. E. Montz. "Population Evacuation: Assessing spatial variability in geophysical risk and social vulnerability to natural hazards." *Narual Hazards Review* (ASCE), 2005: 22-33.

COE. *A Hurricane Evacuation Computer Model for Southeast Louisiana HURREVAC V.6 Documentation and User's Guide.* Baton Rouge, LA: Prepard for the Louisiana Dept. of Military Affairs Office of Emergency Preparedness, 1994.

Cova, T.J. "GIS in Emergency Management." In *Geogrphical Information Systems: Principles, Techniques, Applications, and Management*, edited by M.F. Goodchild, D.J. Maguire, D.W. Rhind P.A. Longley, 845-858. New York: John Wiley & Sons, 1991.

Drabek, Thomas E. "The Evolution of Emergency Management." In *Emergency Management: Principles and Practice for Local Governments*, by Thomas E. Drabek and Gerard J. Hoetmer. Washington D.C.: ICMA, 1991.

Fu, H., and C. G. Wilmot. "Sequential Logit Dynamic Travel Demand Model for Hurricane Evacuation." *Transportation Research Record* (Transportation Research Board) 1882 (2004).

Godschalk, David R. "Disaster Mitigation and Hazard Management." In *Emergency Management: Principles and Practice for Local Government*, by E. Thomas Drabek and Gerard J. Hoetmer. Washington D.C.: ICMA, 1991.

Guangxiang, Cheng. "Friction Factor Functions Calibration for Hurricane Evacuation Trip Distribution." *TRB 2007 Annual Meeting* (Transportation Research Board), January 2007.

HES. *Comprehensive Hurricane Data Preparedness Study Web Site.* September 24, 2003. http://chps.sam.usace.army.mil/USHESdata/HESHOME.htm.

HES. "South Carolina Hurricane Evacuation Study." 2000.

Hobeika, A. G., and B. Jamie. "MASSVAC: A Model for Calculating Evacuation Times Undernatrual Disaster." Edited by Society of Computer Simulation. *Computer Simlation in Emergency Planning.* La Jolla, CA, 1985. 5-15.

Hoetmer, Gerard J. "Introduction." In *Emergency Management: Principles and Practice for Local Government*, by Gerard J. Hoetmer and Thomas E. Drabek. Washington D.C.: ICMA, 1991.

Irwin, M. D., and J. S. Hurlbert. *A Behavioral Analysis of Hurricane Preparedness and Evacuation in Southwestern Louisiana.* Baton Rouge, LA: Louisiana Population Data Center, LSU, 1995.

Janson, B. N., and J. Robles. "Quasi-Continuous Dynamic Traffic Assignment Model." *Transportation Research Record 1493*, 1995: 199-206.

Jones, B., and J. Andrey. "Vulnerability Index Construction: Methodological Choices and their Influence on Identifying Vulnerable Neighbourhoods." *International Journal of Emergency Management*, 2007: 269-295.

KLD Associates. *Formulation of the DYNEV and I-DYNEV Traffic Simulation Models Used in ESF.* Washington D.C.: Federal Emergency Management Agency, 1984.

Lindell, M.K., and C. S. Prater. "Critical Behavioral Assumptions in Evacuation Time Eastete Analysis for Provate Vehicles: Examples from Hurricane Research and Planning." *Journal of Urban Planning and Development* (J), 2007.

Liu, Y., X. Lai, and G. L. Chang. "Two-Level Integrated Optimization System for Planning of Emergency Evacuation." *Journal of Transportation Engineering*, 2006.

MS HES. "Mississippi Hurricane Evacuation Study Behavioral Analysis." 2001.

Murray-Tuite, P. M., and H. S. Mahmassani. "Model of Household Trip-Chain Sequencing in Emergency Evacuations." *Trasportation Research Record* (Transportation Research Boards) 1831 (2003).

Murray-Tuite, P. M., and H. S. Mahmassani. "Transportation Network Evacuation Planning with Household Activity Interactions." *Transportation Research Record* (Transportation Research Board) 1894 (2004).

NWS. *The Saffir-Simpson Scale.* November 28, 2008. http://www.nhc.noaa.gov/aboutsshs.shtml.

Perry, Ronald W. "Managing Disaster Response Operations." In *Emergency Management: Principles and Practice for Local Government*, by Gerard J. Hoetmer and Drabek E. Thomas. Washington D.C.: ICMA, 1991.

Quarantelli, E. L. "The Nature and Conditions of Panic." (The American Journal of Sociology) 60, no. 3 (1954).

RDS. *ExecutiveSummary of a Socioeconomic Hurricane Impact Analysis and a Hurricane Evacuation Assessment Tool (Methodology) for Coastal North Carolina: A Case Study of Hurricane Bonnie.* Greenville, N.C.: Dept. of Sociology and Dept. of Economics, East Carolina Univ., 1999.

Scanlon, T. Joseph. "Reaching Out: Getting the Community Involved in Preparedness." In *Emergency Management: Principles and Practice for Local Government*, by Thomas E. Drabek and Gerard J. Hoetmer. Washington D.C.: ICMA, 1991.

Schmidlin, T. W., B. O. Hammer, P. S. King, L. S. Miiller, G. Thumann, and H. Wetherington. "Use of a Parking Garage as a Hurricane Evacuation 'Refuge of Last Resort'." *International Journal of emergency Management*, 2005.

Sheffi, Y., H. Mahmassani, and W.B. Powell. "A Transportation Network Evacuation Model." *Transportation Research Part A*, 1982: 209-218.

Sosslau, Arthur B., Amin B. Hassam, Maurice M. Carter, and V. W. George. *Quick-Response Urban Travel Estimation Techniques and Transferable Parameters: User's Guide.* Comsis Corporation: NCHRP Report 187, 1978.

Wardrop, J.G. "Some Theoretical Aspects of Road Traffic Research." *Proceedings, Institute of Civil Engineers.* 1952. 325-378.

Wilmot, Chester G., and Bing Mei. "Comparison of Alternative Trip Generation Models for Hurricane Evacuation." (American Society of Civil Engineers) November, no. 24 (2004).